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EG&G Rocky Flats

Task 3 Shallow, High-Resolution Seismic Reflection Profiling in Operable Unit 2 (903 Pad, East Trenches, and Mound) at the Rocky Flats Plant

Final Report

U.S. Department of Energy
Rocky Flats Plant
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TASK 3 SHALLOW, HIGH-RESOLUTION SEISMIC REFLECTION PROFILING IN OPERABLE UNIT 2 (903 PAD, EAST TRENCHES AND MOUND) AT THE ROCKY FLATS PLANT

Final Report

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Submitted to

EG&G ROCKY FLATS, INC

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EXECUTIVE SUMMARY

EG&G Rocky Flats is performing remedial investigations, feasibility studies, and remedial/corrective action projects at the Rocky Flats Plant under the Department of Energy's Environmental Restoration Program Previous remedial investigations conducted at Rocky Flats have identified potential soil, surface water, and groundwater contamination in the vicinity of Operable Unit 2 (OU2) (903 Pad, East Trenches and Mound) Complex stratigraphy and possible structural features underlying OU2 may influence the migration of groundwater Characterizing the complex stratigraphy and delineating structure by conventional drilling methods alone would be prohibitively expensive A cost-effective approach was developed and implemented using shallow high-resolution seismic reflection to acquire detailed subsurface geologic information

The bedrock geology at Rocky Flats was deposited in a low energy delta plain environment of the Late Cretaceous Period The Task 3 high-resolution seismic reflection program delineated anomalous zones defining the limits of channel deposition within the delta plain These anomalous channel zones contain a series of channels where a small stream or a series of small streams meandered back and forth over time Cores from Rocky Flats show that the resulting stratigraphy within anomalous channel zones has a higher percentage of sandstone than in the surrounding delta plain The stratigraphy of the surrounding delta plain consists primarily of siltstones and claystones Although the channel zone sandstones comprise only a small portion of the total sediment volume, they may act as groundwater conduits or pathways for contamination

Three major anomalous channel zones, A, B, and C, were identified and mapped on the high-resolution seismic profiles Two A channel zones, one B channel zone, and one C channel zone were identified The A channel zones lie at the base of the alluvium between 5,940 and 5,900 ft in elevation, approximately 20 to 60 ft in depth This zone is in direct contact with the overlying alluvium and provides a potential pathway for alluvial groundwater to migrate into deeper stratigraphic horizons The B zone lies between approximately 5,900 to 5,850 ft in elevation (60 to 110 ft deep) The B zone is in direct contact with the overlying A zone, thereby providing conduit for contaminant migration to deeper horizons The A and the B channel zones contain claystones, siltstones, and channel sandstones The C zone lies approximately between 5,815 and 5,745 ft in elevation The depth from ground surface to the top of the C channel zone will vary form 110 to 210 ft depending on surface topography No boreholes have penetrated the C channel zone, therefore, its lithology remains unknown The seismic character within the C zone suggests relatively homogenous composition

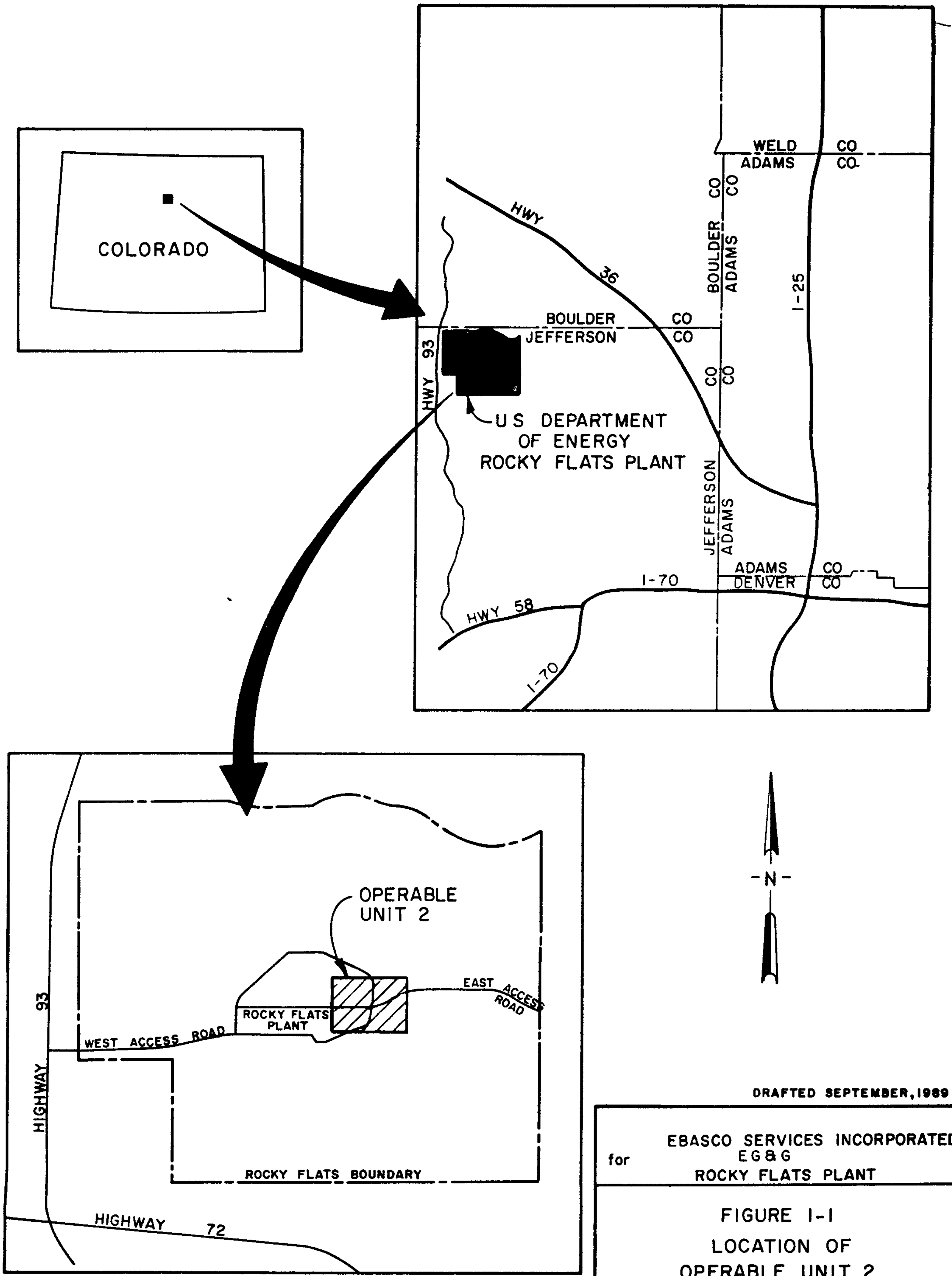
The Rocky Flats Plant is in close proximity to known geological structural features such as folds, faults, and flexures Faults are of major concern because they can provide a conduit for contaminated groundwater to migrate to deeper formations, possibly the Laramie/Fox Hills Aquifer The high-resolution seismic program, although designed to acquire shallow stratigraphic data, suggests but cannot confirm the presence of deeper structures

Past geologic characterizations of Rocky Flats Plant have assumed that the Arapahoe Formation was present immediately below the alluvium The Arapahoe Formation basal sandstones and conglomerates have proven to be a reliable source of water throughout the Denver Basin and are classified as a major aquifer (Romero, 1976) Current geophysical and geological data suggest that the basal Arapahoe sandstones and conglomerates may not be present in the OU2 If the porous Arapahoe Formation is not present, then it is highly unlikely for groundwater from the plant area to contaminate the Arapahoe aquifer elsewhere in the basin

1 0 INTRODUCTION

The Rocky Flats Plant (RFP) is a U S Department of Energy (DOE) nuclear weapons facility operated by EG&G Rocky Flats The RFP is located approximately 11 miles northwest of Denver, Colorado, in northern Jefferson County (Figure 1-1) EG&G Rocky Flats is performing remedial investigations, feasibility studies, and remedial/corrective action projects at the RFP under the DOE's Environmental Restoration Program (ERP) Previous remedial investigations conducted at Rocky Flats have identified potential soil, surface water, and groundwater contamination in the vicinity of the 903 Pad, East Trenches and Mound collectively referred to as Operable Unit 2 (OU2) The stratigraphic and structural features of the bedrock (the solid rock underlying the Rocky Flats alluvium) may influence the potential movement of groundwater Drilling investigations alone can not provide sufficient data to map the stratigraphic complexity of the bedrock underlying OU2 A shallow high-resolution (HR) seismic reflection program was developed and implemented to acquire detailed subsurface stratigraphic information This geophysical program was divided into three subtasks The first task, Task 1, modeled the parameters necessary to collect shallow HR seismic reflection data at RFP (Rockwell, 1989a) The results from Task 1 were favorable, and consequently Task 2 was initiated Task 2 included a field test program that was conducted using shallow HR, common depth point (CDP) seismic reflection profiling Results from Task 2 work not only confirmed Task 1 modeling but also identified the limits of channel deposition in the bedrock (Rockwell, 1989b) In response to the Task 2 recommendations, the following activities were performed to further characterize the bedrock at the RFP

- Thirteen boreholes were drilled near seismic lines to confirm seismic interpretations
- A comprehensive downhole geophysical logging suite was collected in six of the new boreholes
- Synthetic seismograms were generated from the six geophysically logged boreholes and correlated with HR seismic data
- Seismic reflection data were collected in one borehole and processed as a vertical seismic profile (VSP) to provide velocity control for the HR seismic reflection lines



DRAFTED SEPTEMBER, 1989

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FIGURE 1-1
LOCATION OF
OPERABLE UNIT 2

- An additional 12,000 ft of HR seismic data were acquired to confirm the presence and extent of channel deposits

The additional HR seismic profiling was implemented under Task 3 as part of the OU2 geologic and hydrogeologic characterization The location of the HR seismic reflection lines in OU2 is shown in Figure 1-2

During Task 3, HR seismic reflection data were acquired along nine seismic lines (MPS-6 through 14) Data from this task and Task 2 HR seismic lines (Lines 1 through 5), Task 2 VSP data, geophysical logs from six seismic confirmation boreholes, and all available OU2 lithologic logs were combined in an integrated interpretive approach to locate and map the extent of the channel deposits The results from Task 3 HR seismic reflection program are being used by DOE and EG&G as part of the geologic and hydrogeologic characterization of the RFP The integrated data obtained from HR seismic, drilling, and geophysical logs will be used as a decision tool to

1) Resolve hydrogeological problems (map geologic structure and stratigraphy)
2) Provide hydrogeologic data for the design of efficient monitoring systems
3) Optimize future boring and monitoring well placement
4) Select hydrostratigraphic units for future studies (pump tests and water quality tests)
5) Evaluate the construction and effectiveness of corrective action design options for the remediation of contamination

2 0 ROCKY FLATS GEOLOGIC SETTING

The HR seismic program was designed to define sandstone deposits in the upper 200 ft of Cretaceous bedrock The upper 200 ft was emphasized because contaminant migration (if it exists) is most likely to occur in the upper bedrock units The survey was subsequently able to obtain stratigraphic and structual information down to the Pierre Shale All bedrock units down to and including the Pierre Shale are Cretaceous in age (Figure 2-1)

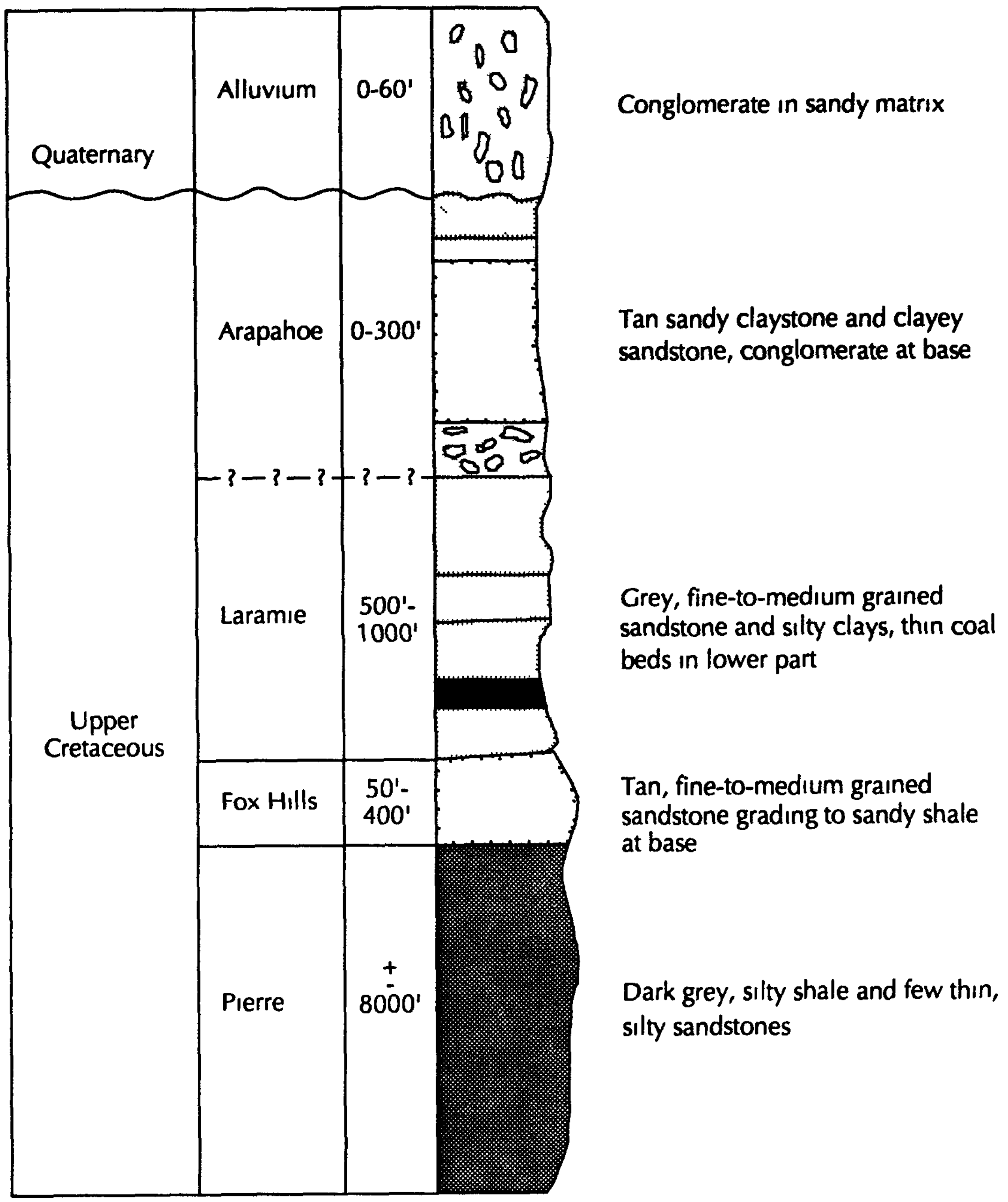

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FIGURE 2-1

GENERALIZED STRATIGRAPHIC SECTION, ROCKY FLATS AREA

After Leroy and Weimer, 1971

The Fox Hills Formation conformably overlies the Pierre Shale The lower portion of the Fox Hills consists of sequences of yellowish-brown to olive-brown sandy shale interbedded with thick layers of limey sandstone at its base The upper portion of the formation consists of medium-bedded to massive, soft to medium hard, olive-brown to tan sandstone interbedded with very thin layers of silty shale (Romero, 1976) The Fox Hills Formation is uncomformably overlain by the basal sandstone facies of the Laramie Formation

The Laramie Formation is comprised of sandstones, siltstones, claystones, and coals deposited in fluvial-deltaic and lacustrine environments (Weimer, 1973) The Laramie Formation can be subdivided into a lower, predominantly sandstone unit with numerous thin coal seams and an upper, predominantly claystone unit Both upper and lower Laramie are exposed in outcrops or present in cores from boreholes west of the RFP (Rockwell, 1987)

The Arapahoe Formation, a fluvial deposit, consists of interbedded conglomerates, sandstones, siltstones, and claystones The sandstones are lenticular and rarely exceed 5 to 8 ft in thickness with a lateral extent of tens of feet The sandstones are quartzose, fine-to-coarse grained, locally conglomeratic, and commonly silty and clayey (Hurr, 1976, Romero, 1976) In Jefferson and Boulder counties, the lower Arapahoe has been described as a conspicuous conglomerate and one of the most recognizable units in the area (Malde, 1955, Weimer, 1973) Averaging 60 to 100 ft thick, this conglomerate contains fragments derived from the crystalline complex farther west and from local sedimentary rocks The conglomerate serves as a stratigraphic marker separating the Arapahoe and Laramie Formations (Figure 2-1)

The Arapahoe conglomerate has been mapped northeast of the RFP on the Jefferson - Boulder county line (Malde, 1955) The conglomerate has been located near the RFP in the Inverness Industrial Park at an elevation of approximately 5,500 ft Projecting the strike of the Arapahoe conglomerate west to the RFP (approximately 5 miles) at a conservative 1 degree dip would put the elevation of the conglomerate at approximately 5,950 ft By this analysis, the basal Arapahoe conglomerate would be expected at or just under the surface of the OU2

Two boreholes (2274 and B218589) in the OU2 have been drilled to a depth of 300 ft The Arapahoe conglomerate was not encountered in either of these boreholes or in any other borehole in the OU2, which leads to the possibility that the geologic unit underlying the Rocky Flats Alluvium is actually the Laramie Formation

Rocky Flats Borehole B304289 penetrated the Fox Hills at a depth of 577 ft The character of the geophysical log in Borehole B304289 suggests the overlying bedrock is lower-to-middle Laramie in age Correlations of this geophysical log to other geophysical logs in the OU2 suggest that either the upper Laramie is present directly under the alluvium or the Basal Arapahoe Conglomerate is not present (Figure 2-2) The absence of the conglomeratic unit at the OU2 may be attributed to one of the following

- The RFP location was relatively high in comparison to the surrounding area, thus deposition of the conglomerate occurred only on the flanks of the Plant area

- The Arapahoe conglomerate at the RFP was eroded away after deposition

- Thrust faulting may have thickened the Laramie Formation and moved the Arapahoe conglomerate farther to the east of RFP

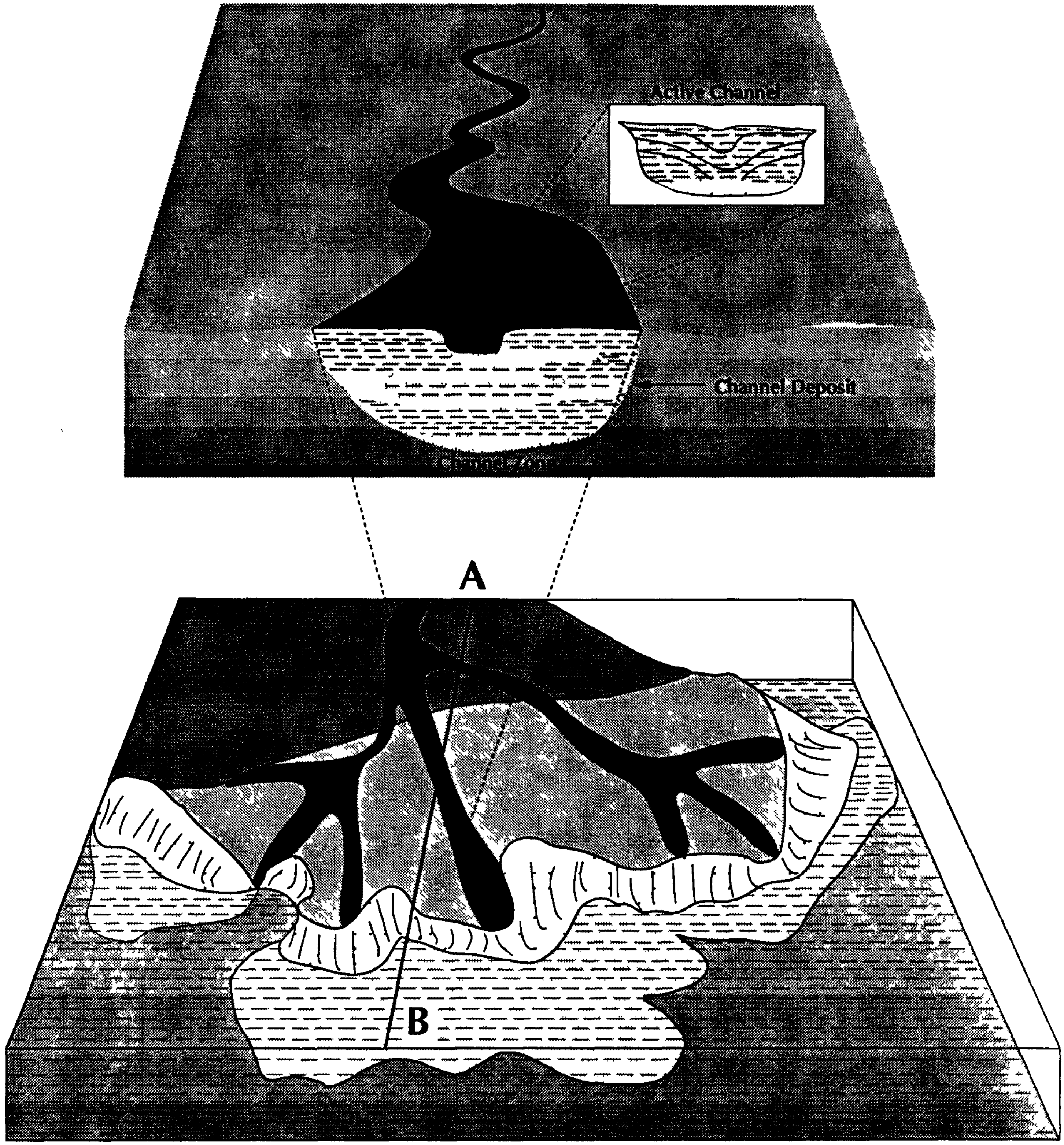
If the Laramie and not the Arapahoe Formation forms the bedrock surface at the RFP, then it is highly unlikely for groundwater from the plant area to contaminate the Arapahoe Formation unless thrust faulting puts Laramie sandstones in direct contact with the Arapahoe Formation east of the RFP This is important because Arapahoe sandstones are more permeable and have a hydraulic conductivity an order of magnitude greater than Laramie sandstones (Romero, 1976) Further investigation is needed to map the Arapahoe Formation at or near the RFP

The Quaternary Rocky Flats Alluvium was deposited unconformably over the erosional bedrock surface of the Arapahoe/Laramie Formations (Rockwell, 1987) (Figure 2-1) The Rocky Flats Alluvium is composed of poorly sorted cobbles, pebbles, and gravels in a sandy clay matrix, deposited in laterally coalescing alluvial fans at the base of the Colorado Front Range Mountains (Hurr, 1976) Calcium carbonate cemented caliche is locally present in the Rocky Flats Alluvium (Rockwell, 1987)

2 1 BEDROCK DEPOSITIONAL MODEL

The predominant lithologies found in boreholes at RFP are claystones, siltstones, and fine-grained sandstones These lithologies indicate a relatively low energy depositional environment According to Davis and Weimer (1976), these Late Cretaceous sediments represent a deltaic environment of deposition Deltaic systems consist of broad and thick deposits of claystones and siltstones of low permeability, along with narrow, thin, and localized deposits of more permeable channel sandstones

A conceptual model of the depositional environment at RFP suggests the presence of low gradient, low energy streams, with banks consisting of cohesive fine-grained sediments derived from suspended load These streams are superimposed upon a more extensive deltaic system (Figures 2-3 and 2-4) This postulated deltaic depositional environment is supported by evidence gathered during the Task 2 HR seismic reflection survey field program Task 2 HR seismic identified anomalous zones that defined the limits of channel deposition On the delta plain a stream or series of streams meandered back and forth, remaining within certain limits controlled by subtle structural features Within the limits of channel deposition (anomalous seismic zones), relatively more sandstone will be deposited than on the rest of the delta plain The major constituents of deltaic deposits are the claystones and siltstones that act as hydrologic barriers or aquitards Although the channel sandstones constitute only a small portion of the total sediment volume, their permeabilities and hydraulic conductivities are greater than the siltstones and claystones, consequently, the sandstones may act as groundwater conduits or pathways for contamination in the anomalous channel zones Task 2 and Task 3 HR seismic reflection data was acquired to map these anomalous channel zones



Legend

- Floodplain
- Deltaic Plain
- Delta Front
- Prodelta
- Marine
- Channel Sediments
- Floodplain Sediments

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Figure 2-3
UPPER CRETACEOUS DELTAIC DEPOSITIONAL MODEL

After Ferm, 1970

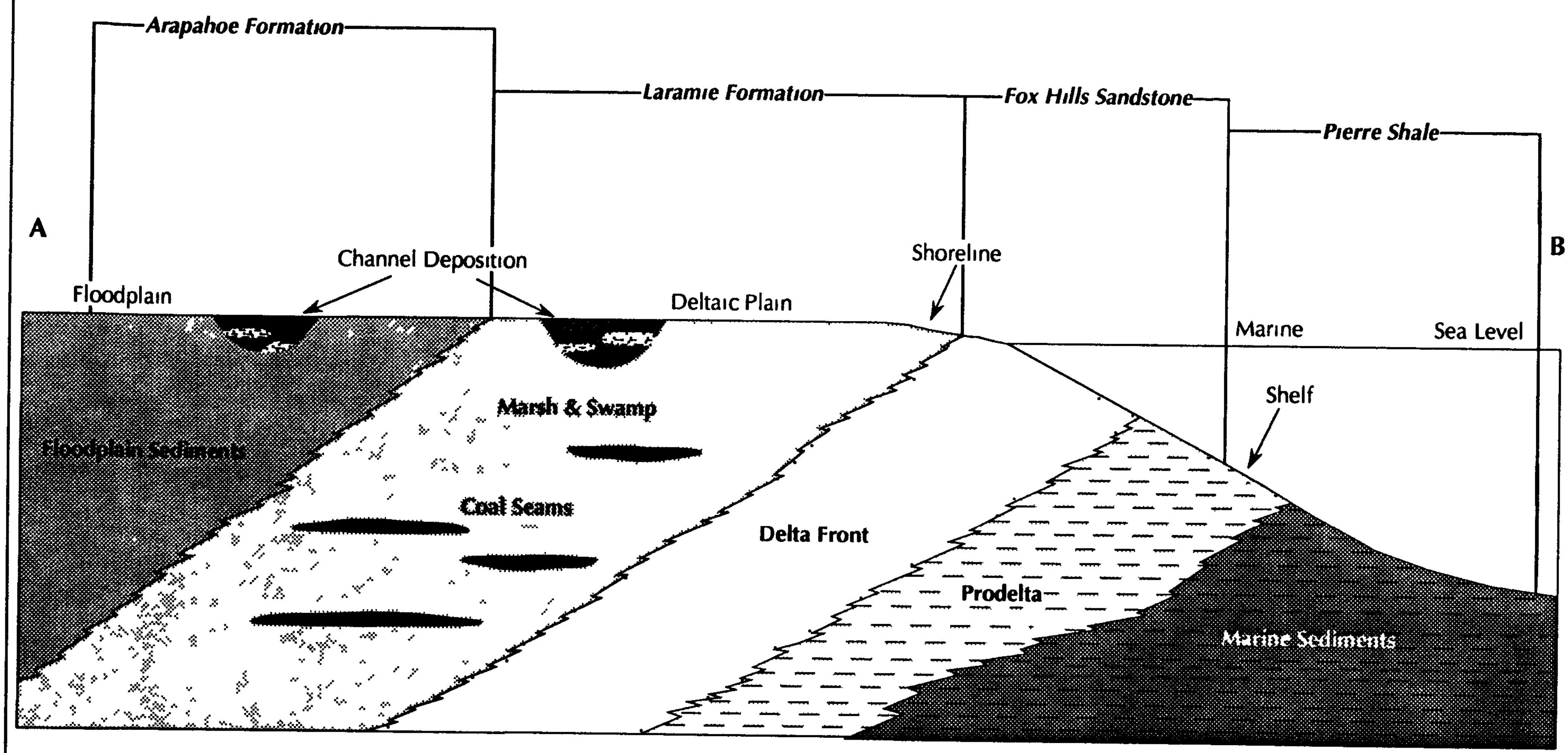

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FIGURE 2-4

UPPER CRETACEOUS DELTAIC DEPOSITIONAL MODEL, CROSS-SECTION A-B

After Ferm, 1970

2 2 GEOLOGICAL STRUCTURES AT ROCKY FLATS

The RFP is in close proximity to known geologic faults Neither the presence nor the extent of faulting at the RFP has been conclusively determined Faults mapped to the north of the RFP have been projected to extend under the Plant site by Hurr (1976) and Kittleson (1989) Reports by Dames and Moore (1981) have indicated that the RFP site is free from faults, although faults have been mapped to the north, by Hurr (1976) and Kittleson (1989), to the west by Davis and Young (1977) and Davis and Weimer (1979), and to the south by Weimer (1973) Structural features observed in the bedrock at RFP were interpreted by Dames and Moore (1981) to be either false leads or "gravity slumps" and growth faults that occurred during deposition in the late Cretaceous prograding delta environment rather than faults attributable to tectonic deformation associated with the Laramide Orogeny In contradiction to Dames and Moore (1981), reprocessing and reinterpretation of seismic data from Colorado School of Mines (CSM) have indicated west-to-east thrust faults under the Plant site in the Pierre Shale (ASI, 1989) On the east side of the RFP in the OU2, borehole data show a thickening in the alluvium due to an approximately 30 ft drop in the bedrock (Figure 2-5) The presence of faults at the RFP are of concern because faults provide possible conduits for contaminated groundwater to flow into deeper formations and possibly the Laramie/Fox Hills Aquifer Proper groundwater remediation depends on locating and delineating faults in this area Parts of the Phase II Geologic Characterization Program are designed to confirm the presence or absence of faults at the RFP

3 0 SEISMIC REFLECTION PROGRAM

Seismic reflection methods are based on the same scientific principles as radar and sonar Seismic reflection profiling consists of a source generating an acoustic wave near the ground surface and recording the acoustic waves that are reflected from subsurface layers and discontinuities The reflected acoustic waves are detected by geophones and recorded by a seismograph

The shallow HR seismic reflection method uses a low-energy source that transmits a wide range of frequencies, high-frequency geophones, and a short geophone station interval (less than 20 ft) The shallow HR seismic reflection method makes it possible to map reflections from beds as thin as a few feet, ranging in depth from 20 ft (or less) to more than 500 ft With this method,complex geological relationships can be interpreted Combined with the CDP method of seismic reflection profiling (Appendix I), it is possible to identify stratigraphic features and make spacial and thickness maps of channel deposits

3 1 PREVIOUS DATA ACQUISITION

The techniques, parameters, and equipment used to acquire data during Task 3 were developed during Tasks 1 and 2 Task 1 modeling determined the best acquisition parameters to obtain shallow subsurface geologic information Task 2 tested and refined the parameters determined during Task 1 Many of the techniques developed during Task 2 were carried through to Task 3 Table 3-1 lists the data acquisition parameters used in Tasks 2 and 3 seismic surveys The total amount of seismic data acquired in the OU2 was 2,500 linear ft in Task 2 and approximately 12,000 linear ft in Task 3

3 1 1 Task 2 Acquisition Techniques

Task 2 HR seismic reflection data (Lines 1 through 5) were acquired using parameters and equipment determined by the Task 1 modeling program Before data collection, several seismic sources and field parameters were tested A noise analysis (or walkaway test) was conducted prior to acquisition of Lines 1 through 5 The purpose of a noise analysis was to determine the velocities, frequencies, and amplitudes of any surface waves In seismic reflection surveying, surface waves represent unwanted events, and care must be exercised to filter out surface waves The results of the noise analysis allowed the design of optimum recording parameters to minimize effects of surface waves

The 2 ft geophone spacing and unbalanced split-spread geometry were used during Task 2, with shotpoints spaced every 4 ft More information on unbalanced split-spread geometry

Table 3-1 Data Acquisition Parameters for Task 2 and Task 3 Seismic Surveys

Geophone Station Spacing	2 ft
Source Spacing	4 ft
Geophones per Station	1
Geophone Frequency	100 Hertz (Hz)
Spread Length	192 ft
Far Offset	120-144 ft
Cable Geometry	unbalance split spread
Number of Recording Channels	96
Sample Rate	0 25 milliseconds (ms)
Maximum Record Length	500 ms
Low-Cut Filter	100-150 Hz
Low-Cut Filter Slope	18 decibels (db)/octave
Alias Filter	720 Hz
Alias Filter Slope	18 db/octave
Common Depth Point Fold	24

can be found in Appendix I A roll-along switch was used to activate geophones at the front of the spread and deactivate geophones at the rear of the spread as data acquisition progressed An unbalanced split-spread arrangement emphasized resolution of the shallower data between depths of approximately 20 and 300 ft The shallow data were collected to delineate channel zones in the upper bedrock where contaminant migration, if it exists, is most likely to occur

3 1 2 Task 2 Acquisition Equipment

An EG&G Geometrics ES-2420 Digital Reflection Seismograph was used for the RFP shallow HR seismic reflection survey This seismic recorder was configured to sample seismic data every 0 25 milleseconds (ms), using 96 recording channels

Custom geophones and cables were used during the Task 2 seismic survey The cables were 120 ft long with geophone connections (takeouts) 2 ft apart The geophones had a resonant frequency of 100 Hertz (Hz), thus being capable of recording the high-frequency energy necessary for the desired resolution

The selection of the energy source was based on several factors including energy output, frequency content, repeatability, portability, efficiency, ease of use, and safety After testing numerous energy sources it was determined the source that best met these criteria and provided optimal data (as determined in Task 2) was an industrial 8-gauge blank cartridge with a 250 to 300 grain charge Industrial 8-gauge cartridges are available with either percussion or electric activation mechanisms Percussion shells were used on a test line and for the VSP in Task 2 Electric cartridges were used for all other data acquisition in Task 2 In either case, the cartridge was detonated in a shot hole 2 to 5 ft below ground surface Electric cartridges were selected for the Task 3 work because the activation mechanism is safer and more reliable

All HR seismic reflection data were recorded to a 9-track computer tape in SEG (Society of Exploration Geophysicists, 1980) D format Field tapes and survey data were sent to Daniel Geophysical for seismic data processing Appendix II describes in detail the equipment used for shallow HR seismic reflection data acquisition

3 2 TASK 3 DATA ACQUISITION

The data acquisition techniques and equipment, proven successful by Task 2, were used in Task 3 with only minor changes During Task 3 the unbalanced split-spread arrangement was slightly modified to emphasize even shallower data, between 20 and 200 ft, and a technique known as undershooting was used

Undershooting was employed in the OU2 to collect seismic reflection data from underneath Central Avenue and through fenced off Solid Waste Management Units (SWMUs) Placing seismic cables and geophones across Central Avenue and through some of the SWMUs was not feasible To collect data from these areas, geophones were placed on one side of the road or SWMU and seismic sources were activated on the opposite side The advantage of this technique is the collection of data without creating traffic delays and without damaging geophones and cables Due to the inherently longer offset distance between the source and receivers, shallow data (the first 100 ms or approximately 225 ft) were not recorded

3 3 DATA PROCESSING

The data processing sequence (Figure 3-1) includes a variety of programs that are normally applied to CDP seismic data After data acquisition and initial data analysis, the exact processing sequence was designed During various steps in the processing sequence, the processing geophysicist consulted with the project geophysicist to ensure data quality Programs in the processing sequence effectively enhance data presentation Programs have many functions including sorting data traces into CDP format, applying static and velocity functions, editing and removing unwanted noise, enhancing frequency content, scaling data for presentation, migrating data to remove raypath imaging problems, plotting data, and a variety

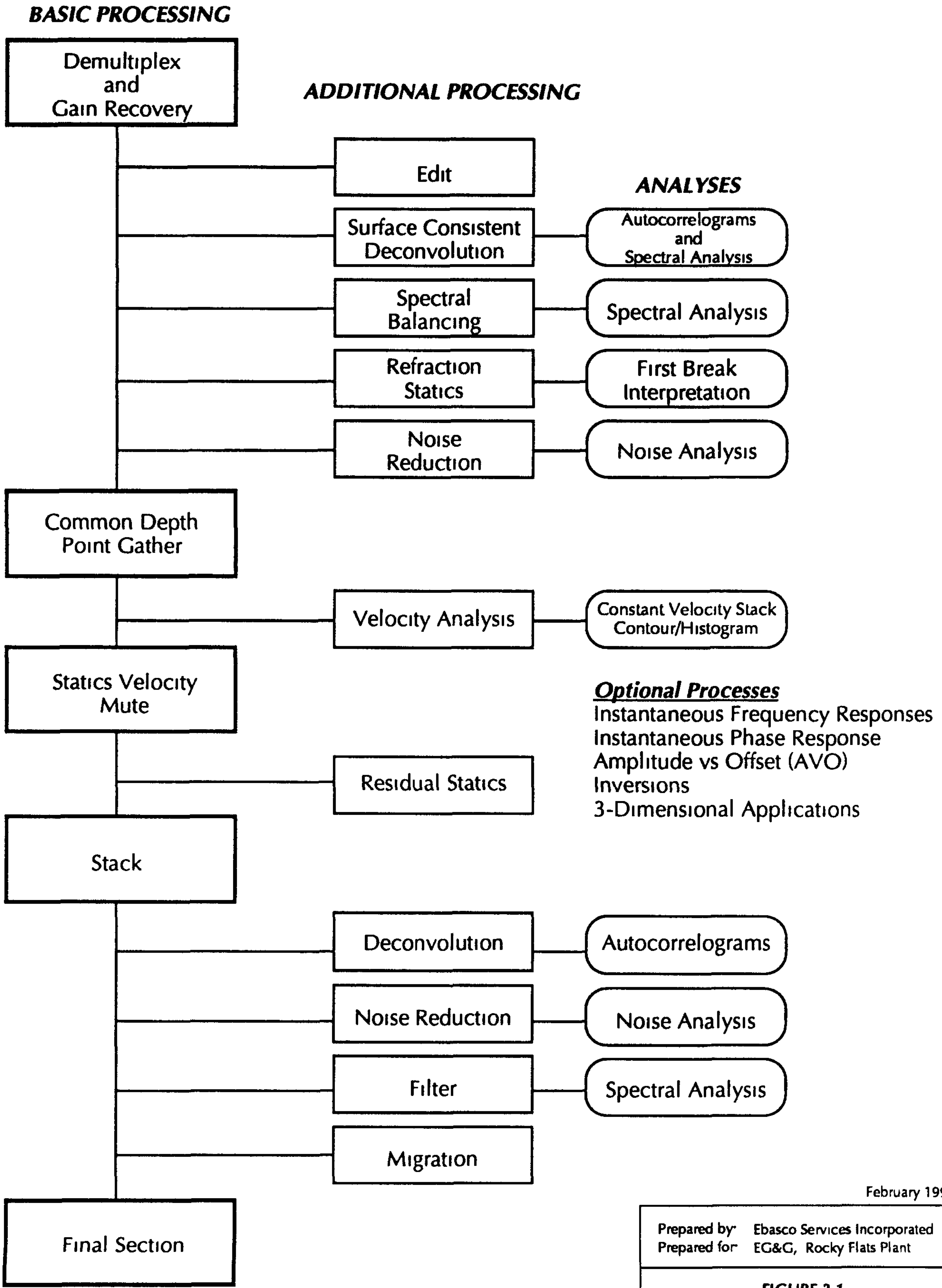

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FIGURE 3 1
SEISMIC DATA PROCESSING ROUTINES

After Sheriff, 1984

of other data analysis techniques A detailed description of the data processing programs used in Task 3 can be found in Appendix III

The end result of the data processing operations was the generation of a two-dimensional seismic profile that represents a geologic cross-section through the earth

3 4 DATA INTERPRETATION

3 4 1 Introduction

The goal of seismic interpretation is to relate seismic events to geologic features Often, particular reflections have distinct characteristics that can be identified and correlated throughout a site For example, a channel deposit that contains interbedded sandstones and claystones is characterized by high-frequency, high-amplitude seismic reflectors, which are caused by the density contrasts between the sandstone and claystone layers A bed of massive sandstone or massive claystone would contain minimal density contrast within that bed, thus few seismic reflectors

The processing and interpretation of the Task 3 data incorporated all the available geologic and geophysical data, including the following

- Seismic velocities obtained from the VSP conducted in Borehole B217489
- The Geophysical log from Borehole B304289 (located approximately 1 mile south of OU2) was used to correlate the lower Laramie and Fox Hill Formations to the seismic profiles
- Geophysical logs from six seismic confirmation boreholes and synthetic seismograms generated from these logs
- Lithologic data from OU2 boreholes and older geophysical logs from Boreholes 2274 and 4086

Geophysical data acquired after the Task 2 program (VSP data and seismic confirmation borehole data) were used to modify and update the interpretation of the Task 2 data

Modified Task 2, Lines 1 through 5, have been included in this report along with the interpretation of Lines MPS 6 through 14

Task 3 acquisition parameters were designed to resolve shallow seismic reflection events and allow better thin bed resolution than Task 2 Task 2, however, has better quality deep data Other differences between Task 2 and Task 3 data quality can be attributed to the following conditions

1) During Task 3, it was often difficult to obtain proper geophone coupling because of frozen ground

2) Borehole drilling operations in OU2 during Task 3 seismic data acquisition generated unwanted seismic noise

On each seismic profile, geologic formations are exhibited in different colors as follows

1) Red denotes Rocky Flats Alluvium
2) Blue denotes Arapahoe/Upper Laramie above the acoustic marker
3) Green denotes Laramie Formation below the acoustic marker
4) Orange denotes Fox Hills Sandstone
5) Brown denotes Pierre Shale
6) Yellow denotes channel zone anomalies The A channel zone is a light yellow, the B channel zone is a darker shade of yellow, and the C channel zone is a golden brown

On the seismic profiles an acoustic marker was interpreted from a change in seismic character Above this marker (denoted in blue on the seismic profiles), the seismic events are generally discontinuous and have low amplitude responses Below this marker (denoted in green on the seismic profiles), the seismic events have stronger and more continuous amplitude responses The different seismic responses indicate a change in lithology Below the acoustic marker are more extensive beds of claystone, coal, and sandstone The acoustic marker was used during interpretation to help define channel zones The channel zones on the seismic lines were defined by their distance above the acoustic marker and their seismic character

The depth and time scale on the side of the seismic profile are in reference to a seismic datum of 5,975 ft In this report, depths to channel zones are given in ft below ground surface and time in ms below seismic datum When relating channel depth to the seismic profiles, the time scale (ms) should be used to avoid converting depths below ground surface to depths below seismic datum The reasons for using a seismic datum are discussed in Appendix I

Borehole total depths (TDs) noted on the seismic profiles are depths below ground surface The depth of borehole penetration is shown on the seismic profiles by a black line starting at the seismic datum (5975 ft above mean sea level) and ending at the approximate TD of the borehole

Deep boreholes penetrating at least 10 ft of bedrock are shown on each corresponding seismic profile by a solid circle Boreholes penetrating less than 10 ft of bedrock are denoted by open circles New borehole identification numbers, placed in use in 1990, are shown on maps and seismic profiles A comparison of old borehole numbers to new borehole numbers is shown on Table 3-2

Boreholes located close to a seismic line are projected into the nearest station on that seismic line, with projection direction and distances noted The depth scale noted on the side of each seismic profile is the approximate depth below seismic datum

Channel Zones

Several anomalous zones are seen on the seismic profiles These anomalous zones most likely represent the depositional limits of broad deltaic channel zones The seismic anomalies do not represent one large channel deposit but rather a series of thin channel-type depositional sequences, as evidenced by a series of high-amplitude, high-frequency events within the shallow anomalous zones Depths to seismic events are computed using estimated seismic velocities These velocities were used to convert the tops and bottoms of the channel zones

Table 3-2 Borehole Identification Numbers

New Number	Old Number
B213789	PZ1389
B215389	6089BRA
B217389	5589BRA
B217489	5689BR
B217589	5789BR
B217689	5889BR
B217789	6089BR
B218189	6189BR
B218589	6289BR
B218689	6389BR
B218789	6489BR
B218989	6689BR
B304289	3789BR
B315289	5989BR
B318889	6589BR
P207689	SEP0489
P207789	SEP0589BR
P207889	SEP0689
P207989	SEP0789BR
P208889	SEP1689BR
P209589	SEP2389BR
P209689	SEP2489BR
P209789	SEP2589
P210289	SEP3189BR
P213889	PZ1489
P213989	PZ1489A
P218389	PZ2789
P219489	PZ1589
P219589	PZ1289

from time to depth Because the velocities are estimated, the depths (below ground surface) of the channel zones are approximate The recorded times in milliseconds of the tops and bottoms of the channel zones are in parentheses next to the approximate depths
The seismic anomalies that have been mapped display three characteristic geometries, each found at different stratigraphic levels on the OU2 profiles These characteristics are

A Channel Zone

The A channel zone exhibits high-frequency, high-amplitude events with many converging or diverging reflectors Converging and diverging reflectors have been interpreted as individual lenses within the channel zone The channel zone margins are defined by dipping seismic reflectors The A channel zone is located on the seismic profiles within the Arapahoe/Upper Laramie, between 175 and 215 ft above the acoustic marker (approximate elevation 5,940 to 5,900 ft)

B Channel Zone

Similar to the A channel zone, the B channel zone is characterized by high-frequency, high-amplitude seismic events with dipping reflectors defining the channel zone margins The B channel zone always underlies the A, however, A channel zones may exist independent of the B channel zone The fact that the A and B channels zones share the same margins is indicative of sedimentation occuring in the same place over a long period of time The A and B channel zones stacked one on top of the other may indicate that this area was topographically low during Cretaceous time The B channel zone occurs at a stratigraphic level between 125 and 175 ft above the acoustic marker, and lies within the Arapahoe/Upper Laramie (approximate elevation 5,900 to 5,850 ft)

C Channel Zone

The C channel zone is bounded on the top and bottom by high-amplitude, low-frequency reflectors, with low-frequency, low-amplitude reflectors located within the channel zone The C channel zone is seen only on Lines MPS-6 and 7 This channel zone is locted on the seismic profile within the Arapahoe/Upper Laramie, 20 to 90 ft above the acoustic marker (approximate elevaton 5,815 to 5,745 ft)

The geometric appearance of a channel zone on a seismic profile is dependent on how the seismic line intersects the channel zone For instance, if the seismic line is perpendicular to the channel zone, the reflectors from the boundaries of the channel zone appear more distinct and show up as concave upward events on the seismic section If the seismic line is oblique or on strike with the channel zone, the characteristic concave upward events become less apparent In those instances the reflectors from the channel zone boundary do not dip as steeply, and the concave upward events appear flattened or stretched out

Interpretation of Seismic Lines

Line 1

The interpretation of Line 1 shows the A channel zone extending the length of the profile The top of the channel zone is 15 ft (20 ms) deep and the bottom of the channel zone is 60 ft (40 ms) deep The B channel zone is interpreted between stations 180 and 225 The top of the B channel zone is 50 ft (35 ms) deep and the bottom is 75 ft (45 ms) deep

Borehole B217589, located at station 112, encountered sandstones between 40 and 57 ft in depth Borehole 39-87, projected from 10 ft north of the line to station 253, also encountered sandstone from 16 5 ft to TD at 22 ft Based on the seismic interpretation, it appears these boreholes both penetrated the A channel zone

Line 2

The A channel zone is interpreted on Line 2 from station 170 to the north end of the line at station 251 It appears that the channel zone may extend further to the north of the line This A channel zone top is 20 ft (20 ms) deep and the channel zone bottom is 45 ft deep (35 ms) From station 175 to station 242 the B channel zone is interpreted underlying the A channel zone The top of the B channel zone is 30 ft (25 ms) deep and the bottom of the B channel zone is 55 ft (40 ms) deep

Borehole 1687BR is projected from 20 ft west of the line to station 180 The lithologic log from this borehole describes interbedded claystones and siltstones with minor amounts of sandstone from the top of bedrock at 23 ft to a depth of 100 ft This borehole projects near the edge of the A and B channel zones on the seismic profile Core data from this borehole may indicate overbank deposits from the A channel zone The borehole also encountered interbedded sandstones and claystones between 100 and 153 ft These lower sandstones are interpreted as part of the B channel zone Borehole 1587, located at station 120, encountered claystone from top of bedrock at 22 ft to TD at 27 ft, which corresponds with the seismic interpretation that no shallow channel zones are present at this location

Line 3

Line 3 is located in the western portion of the OU2 just inside the inner gate At the road (stations 135 to 140) and the utility line (station 163) the seismic source could not be detonated The result is a "skip" or area on the seismic profile where shallow data are missing

On Line 3, the A channel zone extends from station 237 to the west end of the line at station 297 The channel zone top is 15 ft (20 ms) deep and the bottom is 45 ft (35 ms) deep The channel zone may extend further west of the line The A channel zone also intersects the line between stations 191 and 223 at approximately the same depth

Borehole 2387BR located 10 ft southwest of the end of the line penetrated 22 ft of sandstone (from the top of bedrock at 15 ft to 37 ft in depth) This borehole indicates that the A channel zone may extend south and west of the seismic line Borehole 35-87, located at station 224, and Borehole 1787, projected from 10 ft south of the line to station 101, encountered claystone bedrock, which corresponds to the seismic interpretation that no channel zones are present at these locations

Line 4

Channel zone A has been interpreted on Line 4 from station 241 to the end of the line at 297 The channel zone top is 25 ft (20 ms) deep and the channel zone bottom is 60 ft (40 ms) deep It appears the edge of the A channel zone intersects the line again between stations 112 and 148 at approximately the same depth

The B channel zone underlies the A channel zone from station 256 to the west end of the line at station 297 The top of the channel zone is 60 ft (40 ms) deep and the bottom of the channel zone is 85 ft (50 ms) deep It appears both channel zones extend west of the line

Borehole B217489 located at station 275 encountered a thick sequence of sandstones and siltstones from 25 to 90 ft in depth Borehole B217389, located at station 282, also encountered sandstones and siltstones from 26 to 64 ft (TD) No lithologic logs are available from Borehole 2274 projected from 10 ft south to station 123, however, the geophysical borehole logs (natural gamma and neutron) indicate sandstones and siltstones may be present from depths of 28 to 63 ft Borehole 42-86 projected 10 ft from the north to station 118 penetrated 4 ft of bedrock that consists of claystone grading downward into sandstone Seismic character on Line 4 indicates all of the above boreholes penetrated an A channel zone

Line 5

The seismic characteristics representative of the A, B, and C channel zones are not present on this profile

The alluvium at Line 5 is approximately 45 ft (20 ms) thick through the entire length of the line and corresponds to the thickening of the alluvium seen on Lines MPS-10, 11, 12, and 13

Borehole 4086 is projected 14 ft south to station 60 The lithologic log from this borehole describes alluvium to 45 ft, claystone from the top of bedrock to a depth of 77 ft, and mostly sandstone from 77 to 125 ft (TD) The geophysical logs from this borehole show interbedded claystones and siltstones and no clean sandstones Seismic data do not indicate any anomalies associated with this sequence, and no channel zones are interpreted at this location Borehole 3187BR, projected from 60 ft south of the line to station 153, penetrated 45 ft of alluvium, claystone from the top of bedrock to a depth of 72 ft, and interbedded siltstones, sandstones, and claystones from 72 to 140 ft (TD) Based on the seismic interpretation, none of these boreholes penetrated the A, B, or C channel zones

Line MPS-6

On Line MPS-6, initial seismic events slope downward to the south, reflecting the sloping surface topography Of note is the lack of a strong initial bedrock reflector on the south end of the line Based on borehole control in the area, the bedrock surface is approximately 4 ft deep at this end of the line, and acquisition parameters were designed for acquiring data 20 to 300 ft deep, therefore, no bedrock reflection can be seen on the south end of this line

Two channel zones are indicated on the profile The channel zone located between station 156 and station 101 on the north end of the line is stratigraphically between the B and C channel zone horizons The channel zone top is 75 ft (50 ms) deep, and the bottom of the channel zone is 130 ft (70 ms) deep Although it is apparent from the seismic profile that this channel zone extends north beyond the end of the line, no other seismic profile indicates the presence of this channel zone The south boundary of the channel zone is marked by a low-amplitude dipping reflector

The C channel zone has been interpreted at the southern end of the line between station 230 and the south end of the line at station 315 The top of the channel zone is 120 ft (70 ms) deep, and the bottom of the channel zone is 180 ft (102 ms) deep

No boreholes are located immediately near Line MPS-6

Line MPS-7

Line MPS-7 is located in the western portion of the OU2 near the inner gate to the RFP A skip occurs between stations 447 and 485, and another occurs between stations 347 and 368 No shallow data were collected in the area of these skips due to the presence of the east access roads The triangular-shaped skip between stations 292 and 313 is located over buried utility lines

Initial seismic events slope downward to the south, reflecting the sloping surface topography Of note is the lack of a strong initial bedrock reflector on the south end of the line This is because the bedrock surface is only 4 ft deep at this end of the line, and acquisition parameters were designed for acquiring data 20 to 300 ft deep

The interpreted A channel zone extends from station 252 to station 548 The top of the channel zone is 20 ft deep (20 ms), and the bottom of the channel zone is 60 ft (40 ms) deep This channel zone most likely extends across the skips

On the seismic profile, the B channel zone is interpreted to underlie the A channel zone between stations 381 and 530 The top of the channel zone is 60 ft (40 ms) deep and the bottom of the channel zone is 80 ft (50 ms) deep

The C channel zone has been interpreted between stations 796 and 924 The top of the channel zone is at 75 ft (60 ms) and bottom is at 150 ft (90 ms) The seismic character of this channel zone is similar to the C channel zone previously discussed on Line MPS-6 However, there appear to be higher amplitude events within the channel zone on this line, which indicates more heterogeneous material

Borehole 2487, located at station 267, encountered claystone from the top of bedrock to 18 ft (TD) Borehole 2587, located at station 282, encountered 29 ft of sandstone from the top of bedrock to a depth of 44 ft and claystone from 44 ft to 47 ft (TD) Borehole B217689, located at station 325, encountered 30 ft of sandstone from the top of bedrock to a depth of 55 ft Based on the seismic interpretation, these boreholes penetrated the A channel zone In addition, sandstone was encountered from 97 to 103 ft, and interbedded sandstones and siltstones from 205 to 215 ft (TD) in Borehole B217689 The sandstone at 97 ft is located stratigraphically at the lower part of the B channel zone The seismic response of this sandstone is very subtle and does not appear to be very extensive This sandstone is interpreted as either an overbank deposit or a small splay from the B channel zone The deeper interbedded sequence may possibly be overbank material from the C channel zone, however, the seismic character at this location does not match the typical C channel zone character seen at stations 796 through 924 or on Line MPS-6 Based on the seismic interpretation, this borehole did not penetrate the C channel zone

Borehole B217489, projected 60 ft from the east to station 428, encountered a thick sequence of sandstones and siltstones from 25 to 90 ft in depth Borehole B217389, projected 50 ft from the east to station 433, also encountered sandstones and siltstones from 26 to 64 ft (TD) Borehole B315289, located at station 528, encountered interbedded sandstones and claystones from the top of bedrock at 15 ft to a depth of 136 ft, and interbedded sandstones and siltstones from 136 to 220 ft (TD) Based on the seismic interpretation, these boreholes penetrated both the A and B channel zones

The nearest borehole control on the south end of Line MPS-7 is Borehole 1387BRA This borehole, projected 50 ft from the west to station 1024, encountered interbedded sandstones, siltstones, and claystones from the top of bedrock at 4 ft to a depth of 24 ft Stratigraphically these deposits are located between the B and C channel zones

Line MPS-8

Line MPS-8 is located in the central portion of OU2 A skip occurs between stations 350 and 409 No shallow data were collected in the area of this skip due to the presence of the east access road The triangular-shaped skip between stations 228 and 248 is due to a solid waste management unit (SWMU), and the triangular-shaped skip between stations 271 and 282 is located over buried utility lines

The A channel zone is interpreted on the seismic profile between stations 141 and 316 and between station 318 and the skip at station 350 The top of the channel zone is 15 ft (20 ms) deep and the bottom of the channel zone is 50 ft p (50 ms) It appears the channel zone extends further south into the skip

The B channel zone underlies the A channel zone between stations 163 and 265 The top of the channel zone is 50 ft (38 ms) deep and the bottom of the channel zone is 75 ft (48 ms) deep

Borehole 3687BR, projected 10 ft from the east to station 195, encountered bedrock claystone from 8 to 19 ft, and predominantly sandstone from 19 to 74 ft (TD) The seismic interpretation indicates this borehole penetrated the A and B channel zones Borehole 3587, projected 10 ft from the west to station 203, penetrated claystone bedrock from 10 to 14 ft (TD) Borehole 41-87, projected 30 ft from the east to station 216, penetrated claystone bedrock from 15 to 20 ft (TD) Borehole 46-87, located at station 339, penetrated claystone bedrock from 26 to 32 ft (TD) Based on the seismic interpretation, these boreholes are located in the A channel zone but did not penetrate deep enough to encounter the A channel zone sandstones Borehole 45-87, projected 40 ft from the west to station 313, encountered interbedded sandstones and claystones from the top of bedrock at 20 ft to a depth of 40 ft (TD) This borehole is interpreted as penetrating the A channel zone Borehole B217789, located at station 402 (in the skip), encountered mostly claystone from the top of bedrock at 26 ft to a depth of 138 ft However, the geophysical logs indicate a thick (15 ft) interval of sandy siltstone between 68 and 83 ft that corresponds to a possible B channel zone expression between stations 410 and 441 Borehole B215389, located at station 448, penetrated claystone bedrock from 27 to 30 ft (TD)

Line MPS-9

Line MPS-9 is located in the central portion of the OU2 A skip occurs between stations 255 and 335, and another occurs between stations 408 and 446 No shallow data were collected in the area of the first skip due to the presence of a SWMU The second skip lies in the vicinity of the east access road A triangular-shaped skip between stations 460 and 470 is located over buried utility lines

Two A channel zones are interpreted on the seismic profile One is located between stations 110 and 195, between 35 ft (20 ms) deep and 75 ft (50 ms) deep The other channel zone is interpreted between stations 492 and 600, between 30 ft (25 ms) deep and 60 ft (45 ms) deep

Borehole B218989, projected 35 ft from the west to station 245, encountered 13 ft of interbedded claystone and sandstone from the bedrock surface to 30 ft Borehole B218689 is located at station 257 and encountered 9 ft of interbedded claystone and sandstone from the bedrock surface to 25 ft Seismic data in this area do not indicate the presence of a channel zone Sandstone in these boreholes indicates close proximity to a channel zone, and may be overbank deposits from the interpreted A channel zone to the south Borehole B218589, located at station 480, encountered claystone from the bedrock surface to 75 ft indicating no shallow channel zones

Line MPS-10

Line MPS-10 is located in the central portion of the OU2 A large skip occurs between stations 458 and 520 as a result of the presence of the east access road

Of note is the thickening of the Rocky Flats Alluvium on the south end of the line Borehole 55-87, located 30 ft west of Line MPS-10 at station 358, encountered 30 ft of alluvium Borehole 54-87, located 20 ft from the east at station 266, and Borehole 2887BR, located at station 212, encountered 44 ft of alluvium On the seismic profile the alluvium appears to increase in thickness, from 20 ft (15 ms) on the north end of the line to 50 ft (25 ms) on the south end of the line This thickening, due to a step in the bedrock, is also seen on Lines MPS-11, 12, and 13

The A channel zone is interpreted on the seismic profile at the north end of the line between station 588 and the skip at station 520 The seismic expression of the alluvial thickening, seen on the south end of the line, has similar characteristics to the A channel zone (i e , high frequency, concave, upward reflectors) However, the first reflector in the A channel zone has a high amplitude indicating the transition from alluvium to bedrock This high amplitude reflector does not occur in the zone of alluvial thickening The top of the channel zone is 20 ft (25 ms) deep and the bottom of the channel zone is 60 ft (42 ms) deep It appears the channel zone may extend further to the south, however, the channel zone boundary cannot be delineated because of the lack of shallow data in the skip area

Borehole 2887BR, located at station 212, encountered claystone from the top of bedrock to a depth of 100 ft, which corresponds to the seismic interpretation of no shallow channel zones present at this location Borehole 54-87 penetrated 1 foot into claystone bedrock Borehole 55-87 encountered claystone from the top of bedrock at 30 ft to TD at 35 ft Neither of these boreholes are interpreted as penetrating channel zones

<u>Line MPS-11</u>

Line MPS-11 is located in the eastern portion of the OU2 A large skip occurs between stations 442 and 479 and another occurs between stations 503 and 527 No shallow data were collected in the area of the first skip as a result of the presence of the east access road The second triangular-shaped skip is located over buried utility lines

Of note is the thickening of the Rocky Flats Alluvium on the south end of the line Borehole 4086, located at station 242, encountered 45 ft of alluvium On the seismic profile, the alluvium appears to increase in thickness, from 20 ft (15 ms) on the north end of the line to 50 ft (25 ms) on the south end of the line

The A channel zone is interpreted on the seismic profile at the north end of the line between stations 525 and 598 The seismic expression of the alluvial thickening, seen on the south end of the line, has similar characteristics to the A channel zone (i e, high frequency, concave, upward reflectors) However, the first reflector in the A channel zone has a high amplitude indicating the transition from alluvium to bedrock This high amplitude reflector does not occur in the zone of alluvial thickening The top of the channel zone is 20 ft (27 ms) deep and the bottom of the channel zone is 65 ft (45 ms) deep It appears the channel zone may extend further to the south, however, the channel zone boundary cannot be delineated because of the lack of shallow data in the skip area

Borehole 4086, located at station 242, encountered claystone from the top of bedrock to a depth of 77 ft, supporting the seismic interpretation that no shallow channel zone is present at this location

Line MPS-12

Line MPS-12 is located in the easternmost portion of the OU2 A large skip occurs between stations 221 and 253 and another occurs between stations 135 and 165 No shallow data were collected in the area of the first skip as a result of the presence of the east access road The triangular-shaped skip is located over buried utility lines

The seismic character of the A, B, or C channel zones does not appear on this profile However, between stations 398 and 570, a thickening of the Rocky Flats Alluvium is seen Between stations 510 and 515 the alluvium thickens to 55 ft (30 ms)

Borehole B218189, located at station 447, encountered claystone from the top of bedrock at 45 to 53 ft (TD), which corresponds to the seismic interpretation that no shallow channel zone is present at this location

Line MPS-13

The A channel zone is interpreted on the seismic profile from stations 756 to 835, between 20 ft (20 ms) and 70 ft (43 ms) deep, and from station 1145 to the west end of the line at station 1235, between 20 ft (12 ms) and 60 ft (30 ms) deep It appears the channel zone may extend further west of the line

The B channel zone underlies the A channel zone from station 1190 to the west end of the line, between 40 ft (20 ms) and 75 ft (36 ms) deep The B channel zone appears to continue west of the line

The Rocky Flats Alluvium thickens from station 575 eastward to the end of the line On the seismic profile the alluvium increases in thickness from 15 ft (10 ms) west of station 575 to as much as 50 ft (25 ms) on the east end of the line

Borehole B218189, located at station 153, penetrated 45 ft of alluvium and 8 ft of claystone bedrock Borehole 3287, located at station 374, penetrated 47 ft of alluvium and 4 ft of claystone bedrock Borehole 31-87BR, located at station 404, penetrated 45 ft of alluvium, claystone from the top of bedrock to a depth of 72 ft, and interbedded siltstones, sandstones, and claystones from 72 to 140 ft (TD) The sandstone between 112 and 129 ft is seen on the seismic section at 55 ms and exhibits a reflector dipping up to the east This sandstone falls stratigraphically between the B and C channel zones No channel zone anomaly appears on nearby lines 5, MPS-10, or MPS-11 The sandstone may be related to an overbank deposit or an isolated splay Borehole 2887, located at station 512, penetrated 43 ft of alluvium, claystone bedrock from 43 to 98 ft, siltstone from 98 to 118 ft, and claystone from 118 to 207 ft (TD) Borehole 2787, located at station 530, penetrated 42 ft of alluvium and 5 ft of claystone bedrock Borehole B219789, located 30 ft north of Line MPS-13 at station 565, penetrated 40 ft of alluvium and 12 ft of claystone bedrock The lithologies in these boreholes support the seismic interpretation that no shallow channel zones are present at these borehole locations

Borehole B315289, located at station 1186, encountered interbedded sandstones and claystones from the top of bedrock at 14 ft to a depth of 135 ft, and interbedded sandstones, siltstones, and some claystones from 135 to 220 ft (TD) The lithology in this borehole supports the seismic interpretation that A and B channel zones are present at this location

Line MPS-14

Line MPS-14 is located on the north edge of the OU2 A skip is present between stations 1065 and 1084 as a result of buried utilities

The A channel zone is interpreted on the seismic profile from stations 327 to 578, between 20 ft and 45 ft (22 ms) and 55 ft (45 ms) deep The A channel zone is also interpreted from station 605 to 699, between 20 ft (23 ms) and 50 ft (42 ms) deep The edge of the A channel zone is interpreted from station 747 to 805, between 25 ft (25 ms) and 45 ft (38 ms) deep The A channel zone intersects the line from station 963 to 1065, between 20 ft (30 ms) and 50 ft (50 ms) deep The A channel zone on the east end of the line between stations 747 and 1065 resembles the alluvial thickening seen on the east end of Line MPS-13 However, the reflector at top of the A channel zone has a high amplitude, which indicates the transition from alluvium to bedrock This high amplitude reflector does not occur in the zone of alluvial thickening

The B channel zone is interpreted underlying the A channel zone from station 377 to 432 between 50 ft (42 ms) and 85 ft (54 ms) deep

Borehole 3687BR, located at station 390, encountered bedrock claystone from 8 to 19 ft, and predominately sandstone from 19 to 74 ft (TD) The seismic interpretation indicates this borehole penetrated the A channel zone Borehole 3587, located at station 377, encountered claystone bedrock from 10 to 14 ft (TD), it was not deep enough to penetrate the A channel zone

3 4 2 Composite Displays

Composite displays were constructed to relate lithologic and geophysical logs to shallow HR seismic data Composite displays were constructed from geophysical logs acquired in six seismic confirmation boreholes The geophysical logs (sonic and density) were used to create synthetic seismograms From the synthetic seismograms, seismic reflection events can be correlated to known geologic horizons

Sonic and density log data collected through casing are influenced by the casing and do not measure lithologic properties Consequently, the log response in casing was not used in the generation of the synthetic seismogram In all of the seismic confirmation boreholes, casing extends below the A channel zone The A channel zones are correlated from the lithologic logs to the seismic profiles by

1) Taking the known depth of the channel deposit from the lithologic log
2) Converting the depth to seismic time (using velocities from VSP data)
3) Recognizing the seismic character of the A channel zone on the seismic profile

The synthetic seismograms and the seismic profiles collected in the OU2 generally correlate poorly This is probably due to

1) The presence of noise on the seismic profiles
2) The differences between sources used in the acquisition of the seismic data and the sonic log data

Well B217589

The composite display correlating Well B217589 to Line 1 is shown on Figure 3-2 The synthetic seismogram represents the depth interval of 76 to 210 ft The responses on the synthetic seismogram are due to variations in acoustic velocity and density within the claystones and siltstones

Well B217489

The composite display correlating Well B217489 to Line 4 is shown on Figure 3-3 The synthetic seismogram represents the depth interval of 59 to 208 ft The top of the synthetic seismogram at 40 ms corresponds to the top of the B channel zone at 59 ft The high-amplitude response at 42 ms is due to the decrease in acoustic velocity and density between 70 and 75 ft Although the lithologic log shows this interval as sandstone, the geophysical logs suggest that this interval is claystone

Well B217689

The composite display correlating Well B217689 to Line 7 is shown on Figure 3-4 The synthetic seismogram represents the depth interval of 85 to 212 ft At between 50 and 85 ms, the synthetic seismogram responses reflect the density and acoustic velocity differences of the claystones and siltstones in this interval of the well The high-amplitude response at 85 ms is due to the decrease in acoustic velocity and density between 206 and 210 ft Although the lithologic log shows this interval as sandstone, the geophysical logs suggest that this interval is claystone

Well B315289

The composite display correlating Well B315289 to Line 7 is shown on Figure 3-5 The synthetic seismogram represents the depth interval of 76 to 216 ft Casing extends down below both the A and B channel zones, consequently, the synthetic seismogram does not represent their responses The high-amplitude responses on the synthetic seismogram at 58, 68, and 75 ms correspond to the sandstones at 102, 145, and 172 ft, respectively

Well B217789

The composite display correlating Well B217789 to Line 8 is shown on Figure 3-6 The synthetic seismogram represents the depth interval of 46 to 205 ft This well is located in a skip on the seismic line and must be projected to a portion of the seismic profile that has shallow data The high amplitude responses between 55 and 65 ms on the synthetic seismogram correlate to interbedded claystones, siltstones, and sandstones between 113 and 150 ft

Well B218589

The composite display correlating Well B218589 to Line 9 is shown on Figure 3-7 The synthetic seismogram represents the depth interval of 54 to 217 ft The synthetic response at 48 ms is from the sandstone at 92 ft The synthetic response at 70 ms is from the thick sandstone at 170 ft

3 4 3 Results

The integration of all geologic and geophysical data discussed in Section 3 4 permitted the mapping of three distinct channel zones (A, B, and C) in the OU2 Each channel zone is distinguished by its distinct seismic character The A and B channel zones have high-amplitude, high-frequency seismic events, with many events converging or diverging within the channel zone Both channel zones are bounded by dipping events at the channel zone margins Conversely, the C channel zone is characterized by low-amplitude, low-frequency seismic events within the channel zone, and high-amplitude, low-frequency events at the top and bottom of the channel zone

The A channel zone is located between the approximately 5,940 (top of the bedrock) and 5,900 ft in elevation The underlying B channel zone when present always underlies the A, however, A channel zones may exist independently of the B channel zone The lowest base of the B channel zone is approximately 5,850 ft in elevation The C channel zone is seen on only two seismic lines, MPS-6 and 7, and has no subsurface control The C channel zone lies approximately between 5,815 and 5,745 ft in elevation

The thickness of the A channel zone was estimated from the seismic profiles by measuring the time difference between the top and bottom of the channel zone This time thickness, called an isochron, was converted to thickness in feet using an average seismic velocity of 4,000 ft per second (fps) These calculated thicknesses were then contoured to make an isopach map of the A channel zone (Figure 3-8) The isopach maps of the B and C channel zones (Figure 3-9) were made in the same manner using average velocities of 5,000 and 6,000 fps respectively

Two A channel zones are mapped on the western side of the OU2 (Figure 3-8) These channel zones merge in the central portion of the OU2, then diverge into two separate channel zones to the northeast and southeast Based on geologic data and seismic character, the A channel zone consists primarily of sandstones and siltstones deposited in an anastomosing stream environment These deposits are more likely to be hydraulically interconnected, providing a potential bedrock conduit for groundwater contaminants In addition the A channel zone frequently is in direct contact with the overlying alluvium This contact provides a potential pathway for surface water or alluvial groundwater contaminants to migrate into the bedrock

The B channel zone enters the OU2 from the west and bends to the northeast through the central portion of the OU2 (Figure 3-9) The B channel zone has similar seismic character to the A, therefore the B channel zone may have similar hydraulic properties In addition, the B channel zone is in direct contact with the overlying A channel zone, thereby providing another conduit for contaminant migration

The C channel zone is interpreted on Lines MPS-6 and 7 only, and trends east-northeast (Figure 3-9) Because no boreholes penetrate the C channel zone, no conclusions can be made concerning its hydraulic properties The seismic character suggests relatively homogenous composition for the C channel zone

The Rocky Flats Plant is in close proximity to known geological structural features Faults are of major concern because they can provide a conduit for contaminated groundwater to migrate to deeper formations, possibly the Laramie/Fox Hills Aquifer Kittleson (1989) has suggested that thrust faults mapped north and east of the plant may continue under the RFP area Two seismic reflection profiles collected by CSM show thrust faults located under the RFP (ASI, 1989) These faults might displace the Laramie Formation somewhere east of OU2 The HR seismic program was designed to record and process shallow stratigraphic data No major faults were interpreted on the HR seismic reflection profiles in the OU2 to a depth of 500 ft

4 0 CONCLUSIONS AND RECOMMENDATIONS

4 1 CONCLUSIONS

The lithologies found in boreholes at RFP indicate a relatively low energy depositional environment According to Davis and Weimer (1976), these Late Cretaceous sediments represent a deltaic environment of deposition Deltaic systems consist of broad, thick deposits of claystones and siltstones of low permeability, along with narrow, thin, and localized deposits of more permeable channel sandstones

The shallow HR seismic reflection program successfully delineated anomalous areas that define the limits of channel deposition Three major channel zones were identified and mapped in the OU2 The shallower A and B channel zones contain greater volumes of sandstones than the host bedrock These two channel zones may provide potential bedrock contaminant pathways A deeper C channel zone has been identified No boreholes have penetrated this channel zone, therefore, its lithologic and hydrologic properties remain unknown

Geophysical and geological evidence suggests that bedrock sandstones may be Laramie rather than the Arapahoe Formation If this is true, then the potential for contaminating the Arapahoe aquifer is minimal

No major shallow structural features were interpreted in the vicinity of OU2

4 2 RECOMMENDATIONS

It is recommended that several boreholes be drilled to penetrate the A and B channel zones These boreholes should be located near seismic lines to confirm the presence of the channel deposits and to sample potential groundwater contaminants Favorable locations would be the north ends of Lines MPS-9, 10, and 11 near the intersection of Line MPS-14 where no borehole data exist The purpose of a borehole in these areas would be to determine whether the seismic anomaly mapped is an A channel zone or a thicker zone of alluvium Another recommended borehole location is near the 903 Pad at the north end of Line 2 (station 215) If drilling results confirm the seismic interpretation, it is further recommended that additional HR seismic reflection data be acquired to map the areal extent of the channel zones beyond the OU2

It is also recommended that one borehole each be drilled on Lines MPS-6 and 7 to determine the composition of the C channel zone If channel zone deposits are encountered by the drilling, and sampling indicates that the C channel zone is a potential contaminant migration pathway, then it is further recommended that additional HR seismic reflection data be acquired to map the areal extent of the C channel zone structurally updip and downdip from the OU2

It is recommended that the identification of the bedrock formation (Arapahoe or Laramie) in the RFP area be determined through geologic mapping, drilling, and HR seismic reflection data acquisition Since the Upper Laramie sandstones have less hydraulic conductivity than the Arapahoe Formation sandstones (Romero, 1976), the potential for contaminant migration in the Laramie Formation is less

The thrust fault identified on the CSM seismic profiles (ASI, 1989) should be further delineated to the east of the OU2 The possibility exists that a contaminated channel zone could be thrust into contact with a younger, more permeable Arapahoe Formation sandstone, providing another migration pathway

All drill holes deeper than 100 ft should be logged with borehole geophysics to confirm the lithologic logs and to correlate the lithology to the seismic data

The scope of work in Task 3 was to identify and map the shallow bedrock channel zones However, other deeper features that may be channel zones, exist on the seismic profiles and have not been examined It is recommended that additional interpretation be performed to investigate the importance of these features for the geological characterization

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SEISMIC REFLECTION TECHNIQUE

A seismic source generates energy that manifests itself as seismic waves Seismic waves propagate within solids as disturbances traveling through the materials with velocities dependant upon the elastic properties and densities of the materials Typical commercial seismic sources include explosives and vibrating machinery These sources generate two types of seismic waves, body and surface waves Body waves consist of compressional (p) and shear (s) waves Since most of the energy generated by a seismic source is in the form of p-waves, these waves are of primary interest

Seismic wave energy attenuates with distance partly due to frictional heat loss through absorption of energy by the host material Absorption is dependent on the seismic medium, shales have the highest absorption rates, and granites have the lowest Since seismic waves propagate as spherical wave fronts, the wave spreads out over a spherical area Thus, the energy per unit area varies inversely as the square of the distance from the source

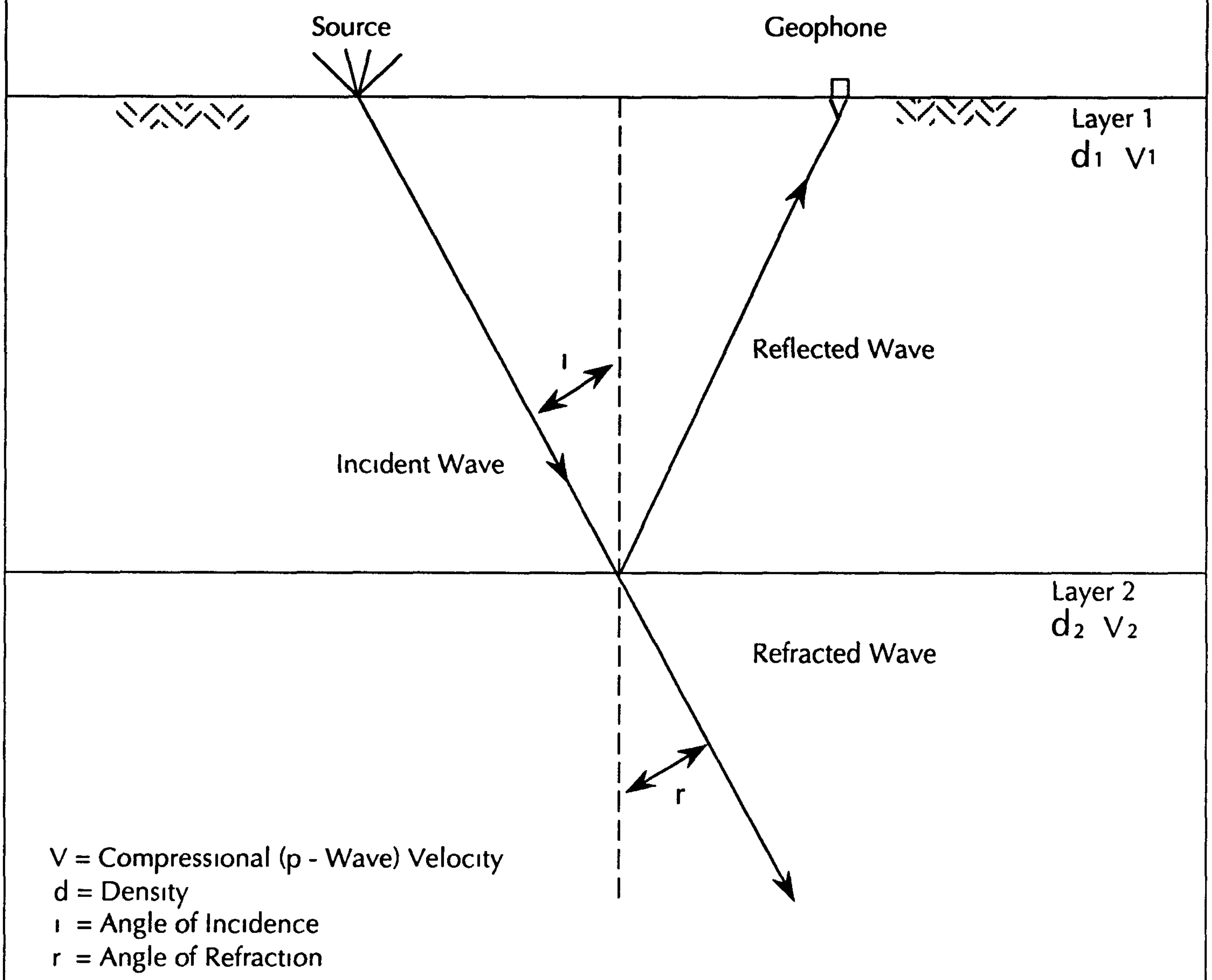
A seismic wave will travel through a medium along a ray path until a discontinuity is encountered A discontinuity can be caused by a change in lithology or fluid content of a porous medium At a discontinuity, part of the wave will be reflected and another part refracted in accordance with Snell's Law as illustrated in Figure A-1

The relative amplitude of a reflected wave from the boundary of two layers, Layer 1 and Layer 2, can be expressed in the form

$$R = \frac{d_2 V_2 - d_1 V_1}{d_2 V_2 + d_1 V_1}$$

where

R = reflection coefficient
d = density in grams per cubic centimeter of medium
V = velocity of p-wave through medium



February 1991

Prepared by Ebasco Services Incorporated
Prepared for EG&G, Rocky Flats Plant

FIGURE A-1

GEOMETRY OF SNELL'S LAW

The product of the density and velocity is known as the acoustic impedance If the acoustic impedance increases across an interface, then the reflected wave has a positive amplitude Conversely, if the acoustic impedance decreases across an interface, the reflected wave has a negative amplitude

The refracted p-wave makes an angle, r, expressed by the relation

$$\frac{\sin i}{\sin r} = \frac{V_1}{V_2}$$

When $\sin i = V_1/V_2$, $\sin r$ becomes unity and r becomes 90° The refracted wave does not penetrate the medium, but travels along the interface between the two materials Angles i and r are measured relative to the normal at the intersection of the interface and the incident wave

Where seismic waves strike any irregularity along a surface such as a corner or a point where there is a sudden change of curvature, the irregular feature acts as a point source radiating waves in all directions Such radiation is known as diffraction The amplitude of a diffracted wave falls off rapidly with distance away from a source

Another seismic phenomenon, the interbed multiple reflection is illustrated in Figure A-2 A wave reflects upward from the interface between Layer 2 and Layer 3 Returning to the surface, the wave reflects downward from the Layer 1 - Layer 2 interface, because any change in acoustic impedance at an interface boundary can cause a reflection The wave again reflects from the top of Layer 3 and successfully returns to the surface

Figure A-2 also shows the types of seismic waves generated by a surface source that will be detected by a geophone The air wave travels at the speed of sound in air (approximately 1,100 ft/second) The direct wave travels from the source to the geophone within the uppermost medium This wave is normally faster than the air wave but slower than the other illustrated waves The refracted wave has the earliest arrival time The reflected wave is slower than the

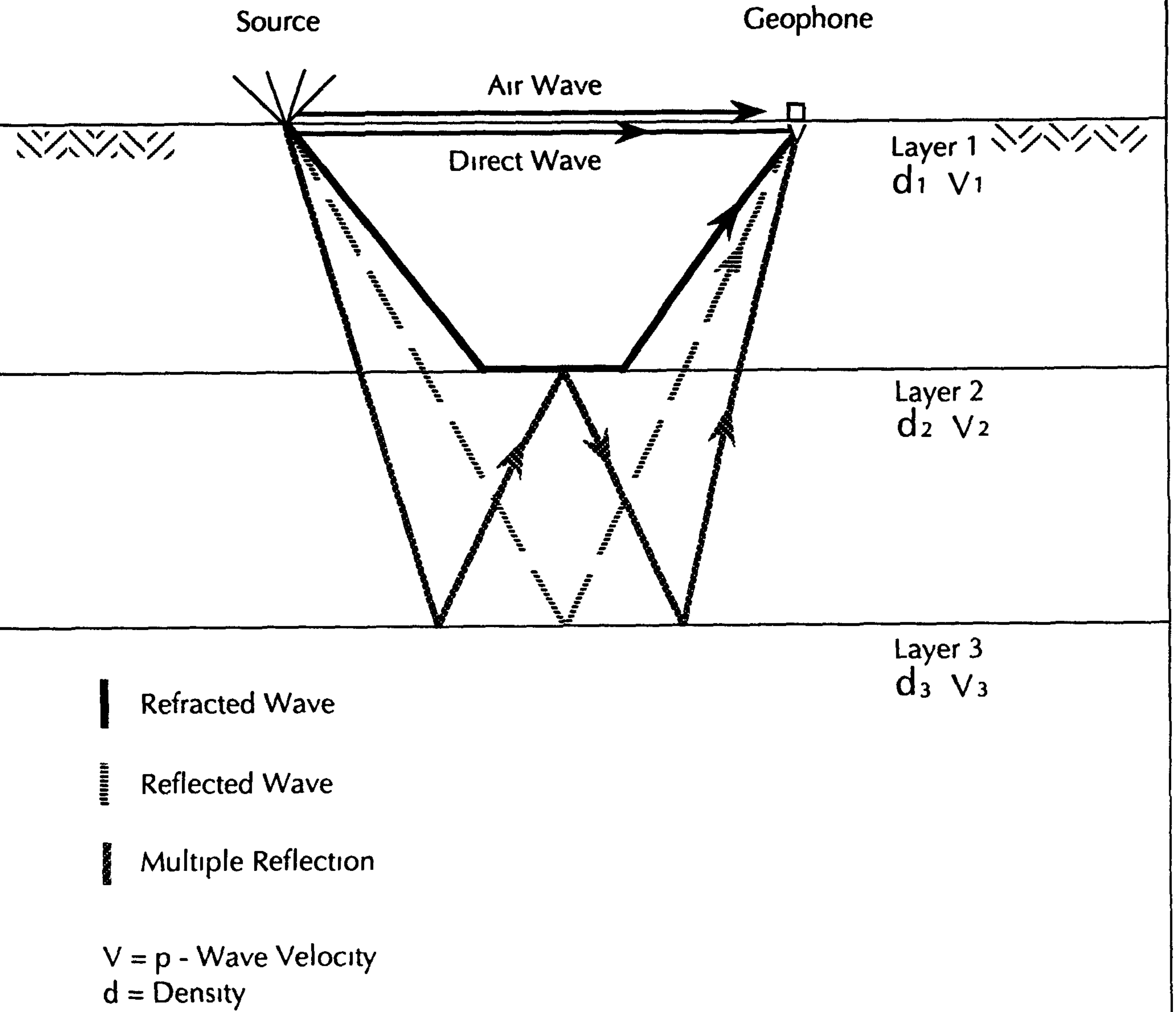


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FIGURE A-2

TYPES OF SEISMIC WAVES

refracted wave A multiple reflected wave has a longer arrival time than the reflected wave because of the greater distance traveled Because of the varying velocities of the different waves it is possible to design seismic field parameters to record the waves of primary interest

According to signal theory, the amount of information present in a seismic reflection signal is proportional to the bandwidth The bandwidth of a seismic signal is the range of frequencies contained within The maximum frequency that can be recorded reliably is equal to one-half of the sampling frequency or rate This is known as the Nyquist frequency At a 0 25 ms sampling rate, the Nyquist frequency is 2,000 Hz

COMMON DEPTH POINT METHOD

Seismic reflection techniques build on basic seismic principles Development of digital recording techniques in the 1960s catalyzed great advances in seismic reflection acquisition, processing, and interpretation Seismic noise is any unwanted signal sometimes it is random and other times it is coherent (e g , an operating water pump or a nearby electric powerline) To reliably interpret a seismic event, the S/N ratio must be at least 1 1

The Common Depth Point (CDP) technique has enabled the recording and display of reflection events that have S/N ratios less than unity The CDP technique records reflections from multiple offsets at different source and receiver pairs as illustrated in Figure A-3 For each CDP the number of source and receiver pairs recorded is called the fold Six fold data, also called 600 percent stack, has six source and receiver pairs The S/N ratio doubles for each quadruple increase in the CDP fold The CDP fold can be calculated by

$$\text{CDP fold} = \frac{\text{receiver spacing}}{2 \times \text{source spacing}} \times \text{number of recording channels}$$

The processing of seismic reflection data is a statistically intensive procedure and requires human guidance at each step After acquisition, the seismic reflection data are processed from source

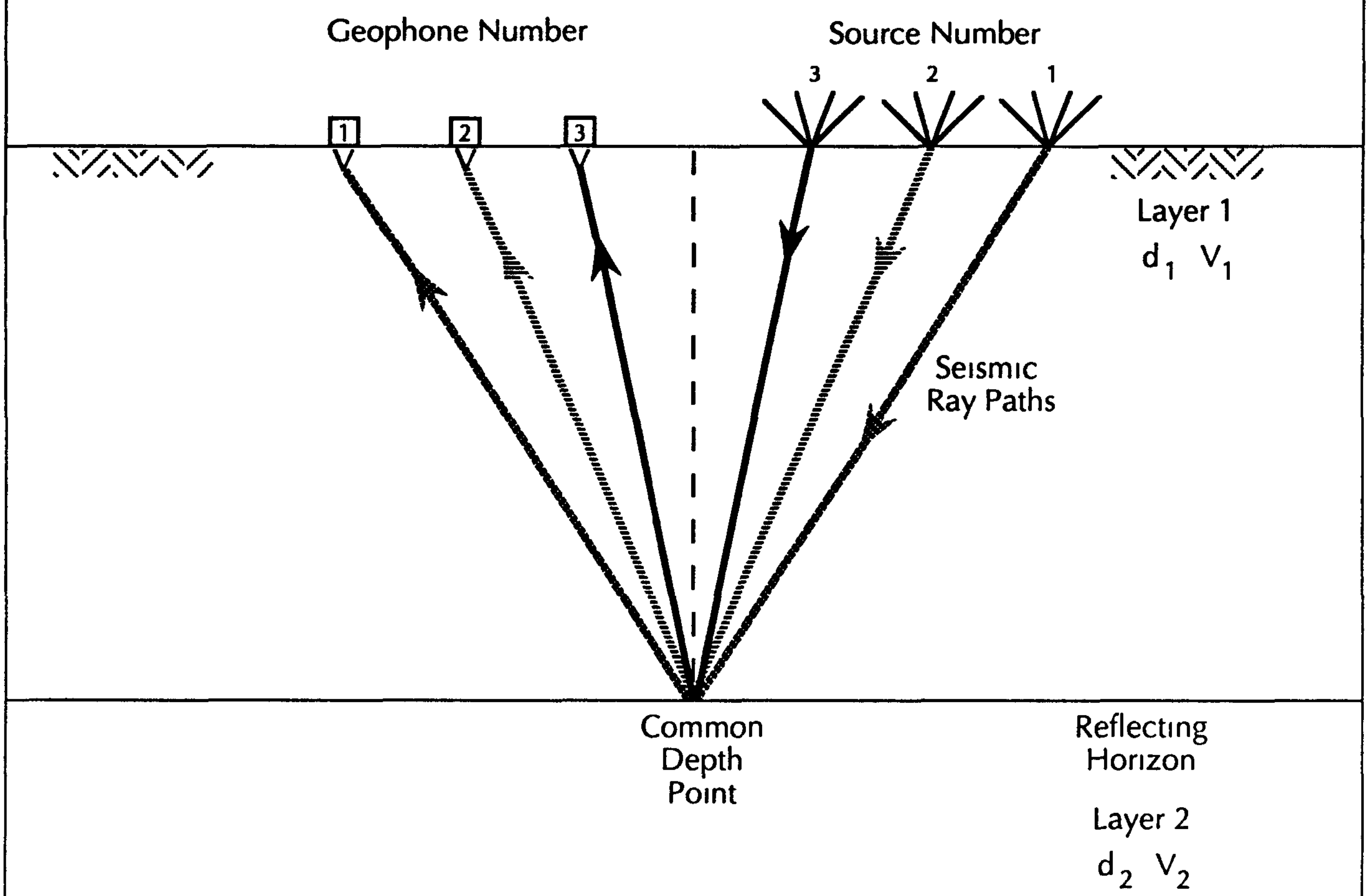

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FIGURE A-3

COMMON DEPTH POINT TECHNIQUE

record format into CDP record format Each CDP record will have the same number of traces equal to its fold Because the distance between source and receiver is greater for the longer offsets of a reflection event (source-receiver 1 as opposed to source-receiver 3, Figure A-3), the recorded reflection event itself will record at a later time The difference in time for a particular event on adjacent traces is termed normal moveout Data are corrected for normal moveout during processing, and all traces in the CDP record are merged or summed together (stacked) This enhances the real events and cancels undesirable random noise, thus increasing the signal to noise ratio (S/N)

Before stacking, data are corrected for elevation variations, resulting in a static correction After stacking, automatic statics are performed to correct for velocity variations in the near-surface weathered layer Digital filters are applied at various steps in the processing to eliminate undesirable noise and enhance the reflection events Post-stack filtering may include enhancing individual reflection events to improve the interpretation by statistically comparing adjacent seismic traces for continuous events versus random noise

Seismic events recorded from a geophone appear to arrive from directly beneath the geophone Where the reflecting horizon is dipping, the position of the event is incorrect Dipping events migrate downdip If necessary, these events can be migrated back to their true location Depending on the data and objectives of the interpreter, this process can be done either before or after stacking (pre-stack or post-stack migration)

Recording shallow reflection events requires modification of standard seismic reflection techniques In standard seismic reflection techniques 12 or more geophones are grouped together as an array Typical distances between groups are tens to hundreds of ft In shallow HR seismic reflection work geophone arrays are eliminated and individual geophones are used Geophone spacings are reduced to a few ft, depending on the depth to the shallowest target Shallower targets require closer geophone spacings The number of recording channels needed is dependent on the depth to the deepest target of interest and the geophone and source spacing Vertical resolution is limited by the bandwidth of the recorded signal and the sampling frequency Horizontal resolution is limited by the bandwidth of the recorded signal and the geophone spacings

SEISMIC DATUM

The seismic datum is an arbitrary reference surface that corrects seismic data for local topographic variations The start time of each record is corrected to the seismic datum In general, if this reference datum is below the surface then some shallow data will be lost If the datum is above the ground surface then the earliest seismic events are recorded and preserved on the seismic profile Conventional seismic reflection utilizes a seismic datum below the surface because there is little interest in shallow events, however the Task 2 and 3 seismic programs were particularly interested in the early or shallow events Therefore a seismic datum above the ground surface was used For example, a borehole has an elevation of 5900 ft The seismic line intersecting the borehole has a seismic datum elevation of 5975 ft A sandstone was encountered in the borehole at a depth of 120 ft The seismic depth of the sandstone is 195 ft on the seismic profile because the seismic datum is 75 ft higher than the borehole ground surface elevation

INSTRUMENT SPECIFICATIONS

- EG&G Geometries ES-2420 Digital Reflection Seismograph
- Mark Products L-40 A-2 Geophones
- Input/Output RLS-240M Rota-Long Switch
- Input/Output Synchrafone I and II Source Synchronizer
- Mountain Systems Service Geophone String Tester

In the event of unforeseen circumstances, equivalent instruments will be substituted for equipment listed below

EG&G GEOMETRICS ES-2420 DIGITAL REFLECTION SEISMOGRAPH

The following specifications apply to an operating environment of 0 to 40 degrees C, after a 5 minute warmup period (Source EG&G Geometrics, 1984)

Analog Performance Specifications

Preamplifier Gain	32 (30 1 db)
	64 (36 1 db)
	128 (42 1 db)

Selected by switches on printed circuit board

Input Impedance	Differential, 20K ohms, 01 ufd
	Common Mode, 5K ohms, 02 ufd

Maximum Differential	@ 30 db, 0 640 volts (V) peak to peak
Input Voltage	@ 36 db, 0 320
	@ 42 db, 0 160

Maximum DC Common Mode
Voltage 10 0 V

Transient Protection Transients with energy less than 0 75 Joule and voltage less than 200 V will not damage instrument

Alias Filters	6 db Frequency	Stop Band Frequency	Stop Band Attenuation
	45 Hz	125 Hz	80 db
	180	500	80
	360	1000	78
	720	2000	78
	1440	4000	78

6 db corner frequency tolerance	3% max
Time delay, constant from 5 Hz to Fc within	± 2%
Time delay similarity between channels	± 2%

Low Cut Filter Frequency 5 to 320 Hz in 5 Hz increments
3 db corner frequency tolerance 3% max
Type Butterworth
Attenuation slope 18 db/octave

Notch Filter 50 or 60 Hz or out, selected from front panel
6 db bandwidth 9 Hz typical $F_o \pm 3$ 65 min ± 6 80 max
50 db bandwidth 0 5 Hz typical $F_o \pm 0$ 1 min

Floating Point Digitizer

Instantaneous-floating-point amplifier with 16 gain ranges (6 db per step) followed by a 15-bit analog-to-digital converter Amplifier gain range is automatically selected for each sample to maximize the precision of the mantissa value

Exponent	4-bit unsigned binary number representing the gain range, where zero represents maximum gain (minimum signal)
Mantissa	15-bit, twos-complement binary
Full scale input voltage	± 10 24 V
Gain step relative accuracy	0 1%
Analog/Digital (A/D) converter accuracy	0 2%
A/D converter linearity	0 01%

System Response

Signal to Noise Ratio	100 db (3 to 180 Hz, 42 db preamp gain, 600 ohm input, notch & low-cut filters out, alias filter set to 180 Hz)
Frequency Response	Lower 3 db frequency, 1 6 Hz ±10% Upper 3 db frequency, determined by alias filter
Gain accuracy	1%
Gain similarity between channels	2%
Total Harmonic Distortion	0 05% FPA in minimum gain Preamp gain minimum Input 0 226 voltage root mean square (Vrms) 3 to 1000 Hz
Crossfeed	<80 db, 3 to 2000 Hz
Timing	Time base accuracy 0 002%

Sample skew	Within 8 channel group, 1/40 ms/channel

Operating Characteristics

Sample Interval, write-to-memory	1/4, 1/2, 1, 2, or 4 ms Front panel selectable
Real time clock	Built in digital clock with time of day and day of year Battery backup provides continuous timekeeping Basic accuracy 3 seconds per month at 25 deg C Time recorded on tape
Maximum Record Length	Set from front panel to maximum of 99 seconds in direct-to-tape In stack-to-memory maximum length determined by sample interval 1/4 ms 4 096 seconds 1/2 8 192 1 16 384 2 32 768 4 65 536
Delay Start	Postpones sampling of data by front-panel selected delay up to 9 999 seconds in 0 001 second increments
ES2420 Acquisition Control Unit (ACU) Power Supply	Operates from 10 to 18 V DC
DP2420 Printer Power Supply	Operates from 10 to 14 V DC
DMT2420 Tape Drive Power Supply	Operates from 10 to 16 V DC

Dimensions

ACU	28 x 16 x 23 5 inches (22 5 with 71 x 41 x 60 cm cover removed)
Expansion Module	same as ACU
Portable Tape Deck	same as ACU

Plotter	15 x 15 x 18 inches 38 x 38 x 46 cm

<u>Weights</u>

Acquisition Control Unit	110 lbs (50 Kg) with 4 channels 7 lbs (3 Kg) for each additional 8-channel board set
Printer	40 lbs (18 Kg)
Portable Tape Deck	100 lbs (45 Kg)
Environmental	Operating temperature, 0 to 45 deg C continuous operation with built-in forced air cooling Can be operated in cyclic conditions to temperature of 50 deg C Storage temperature - 40 to 70 deg C Humidity 10 to 95% non-condensing May be operated in vertical position in light rain (cover closed on tape recorder, protection for plotter) Weatherproof with transit lid closed

<u>CRT Display</u>

512 by 512 dot matrix graphic display of seismic data and acquisition parameters Can display at maximum expansion of one dot per sample, or compressed in 3 db steps up to maximum of 16,196 samples on screen Also displays a time cursor and scale lines and selected parameters (battery voltage constant, file number, and status messages)

TAPE DATA FORMAT

Tape format	Nine-track, SEG D, 2 1/2 byte, multiplexed
Data density	1600 bits per inch (bpi)

Block size	Fixed blocking, equal to an integral number of scans, as close as possible to a user selected maximum or ungapped
Channel set descriptor	One for all channels
Sample skew	Not written to tape For each set of Channels (usually 8) supported by a Data Acquisition Memory (DAM) board - Preamplifier Filter (PF) board pair, sample skew starts at zero and increased by 1/40 ms per channel The maximum sample skew for any channel in the system is thus 7/40 ms
Data word	Ones complement, twenty bits with a one-bit sign, four-bit binary exponent, and 14-bit mantissa The least significant bit (LSB) is zero

GEOPHONE SPECIFICATIONS - MARK PRODUCTS L-40 A-2

The following specifications are found in the operatiosn manual (Mountain Systems Service, Undated)

Standard Frequency Range	100 Hz
Frequency Tolerance	$\pm$ 7%
Standard Coil Resistance $\pm$ 10% (Ohms)	325, 510, 780
Distortion @ Resonance, @ 0 7 in/sec	0 2% MAX
Transduction Constant, V/in/sec	0 031 Rc
Open Circuit Damping	$\frac{47\ 9}{f}$
Coil Current Damping	$\frac{20\ 8\ Rc}{f\ (Rc + Rs)}$
Suspended Mass, Grams	5 7
Case-to-Coil Motion, p-p in	0 080
Intrinsic Power Sensitivity milliwatts (mw)/in/sec	0 96
Basic Unit Diameter, in	1 25
Basic Unit Height in	1 37
Basic Unit Weight oz	5 0

ROTA-LONG SWITCH SPECIFICATIONS - INPUT/OUTPUT RLS-240 M

The following specifications are presented in summary form from the operations manual (Input/Output, Inc , 1981a)

- 240 input stations
- 120 recording channels
- Unlimited types of recording configurations
- Auxiliary connector permits diagnostic cable tests with an ohmmeter or I/O Break Chek
- Size 20 in wide x 20 in tall x 6 50 in deep
- Weight 40 lbs

SYNCHRAFONE - INPUT/OUTPUT SYNCHRAFONE I AND II SOURCE SYNCHRONIZER

The following specifications are presented in summary form from the operations manual (Input/Output, Inc , 1981b)

- Contains radio within unit
- Four privacy codes
- Digital display of uphole time
- Time break and uphole time output from Encoder
- Firing time repeatability at 1 ms
- Available as truck mount or portable
- Wire line and radio modes

REFERENCES

EG & G Geometrics 1984 ES-2420 Digital Reflection Seismograph Operation Manual

Input/Output, Incorporated 1981a RLS-240M Manual Rota-Long Switch Operations Manual, 12 pp

Input/Output, Incorporated 1981b Synchrafone Series Operations Manual, 111 pp

Mountain Systems Service Undated Geophone String Tester (GST) Operators Manual, 10 pp

PROCESSING INFORMATION PRESENTED ON A SEISMIC REFLECTION PROFILE

Labeling on a seismic reflection profile (section) indicates the type of seismic reflection data and provides information about the field acquisition parameters and the data processing steps As shown for Line 8 the label is located on the right side of the seismic section Above the actual reflection data, the surface topography is presented

SIDE LABEL

At the top of the side label on the far right of the section indicates the name of the client ordering the data processing services, i e Ebasco Services Inc for EG&G Below the client name is the seismic line identifier, i e Line MPS-8 The prospect "Rocky Flats" designates the area of data collection The county and state location are given beneath the prospect name Below the prospect location is a directional arrow pointing towards the beginning of the line with the cardinal direction denoted (in this case, north) Below the north arrow is the seismic data processing center's logo, i e Daniel Geophysical, Inc

RECORDING PARAMETERS

Line 1 of the side label indicates the recorder of the seismic data, i e , Ebasco Services and the recording date, January and February 1989

Line 2 indicates the instrument manufacturer and model, i e , EG&G 2420 and the sample rate (the time interval at which each seismic channel is polled for a data value)

Line 3 indicates the type of gain or amplifier setting for each channel The EG&G 2420 seismograph has a 16-bit analog to digital converter with instantaneous floating point (IFP) gain The amplifier setting for each channel is adjusted dynamically by the seismograph based on the input signal amplitude Line 3 also indicates the type of seismic source used, i e 8-gauge electric capsule

Line 4 indicates the explosive array (source pattern) Seismic reflection surveys may utilize more than one source of the same type simultaneously The source pattern can be in-line or in a geometric pattern, such as a rectangle In this case the source was located 5 feet perpendicularly off the line Line 4 also indicates the charge size, i e 300 grain

Line 5 shows the recording tape format, the SEG-D 1600 BPI The SEG-D format is the standard magnetic tape format 'D' as specified by the Society of Exploration Geophysicists (SEG, 1980) 1600 BPI means a recording density of 1600 bits per inch Line 5 also gives the shot hole depth (or shot burial depth)

Line 6 on the left shows the number of traces or recording channels used and the source interval The source interval is the ground distance between successive seismic shots

Line 7 shows the record length This is the total time (500 milliseconds [ms]) that the seismograph recorded Line 7 also shows the geophone interval, the distance between each geophone on the ground

Line 8 shows the elapsed time This is the amount of time that elapsed while the seismograph was recording, but before the seismic source was activated (50 ms) Sometimes a delay in the shot detonation is added to ensure that the source timing mechanism (synchronizer) is properly synchronized with the seismograph Line 8 also shows the station interval to be 2 ft This is the ground distance between receiver (geophone) stations

Lines 9 through 14 (left side) shows the recording filter settings The low-cut filter is given as the frequency start of the attenuation of lower frequencies The low-cut filter slope is the rate of attenuation The high-cut filter is the frequency start of attenuation of higher frequencies The filter slope for the high-cut filter is also shown The last filter item is the notch filter When recording in areas near electric power lines, excessive 60 Hertz (Hz) noise can be rejected using the notch filter inches (in)

Line 9 (right side) shows the geophone array to be "single in-line " This means that a single geophone was used at each receiver station

Line 10 (right side) shows the geophone's natural resonant frequency, i e 100 Hz This is the vibration frequency of the geophone in the absence of an oscillatory disturbing force

Line 11 (right side) displays the seismic line orientation

Line 12 (right side) shows that trace one (i e , the first seismic trace) starts on the south end of the seismic line

Line 14 (right side) indicates the Common Depth Point (CDP) fold, in this case 24 fold

At the bottom of the recording parameters box is a diagram of the geophone cable geometry It shows the shotpoint location in reference to the seventh trace location, the first trace location in reference to the shotpoint, and the last trace location in reference to the shotpoint

PROCESSING SEQUENCE

The next large box displays the final processing sequence The functions of each process are discussed later in Appendix III

DISPLAY PARAMETERS

The display parameters box describes the manner of displaying the seismic section The number of seismic traces displayed per inch is 10 The vertical scale is 50 inches per second (i e one second of data requires 50 inches to display) The seismic polarity is normal Reverse polarity is the other option and means that the final amplitude of the seismic traces has been multiplied by -1 For stratigraphic interpretation of seismic reflection data it is sometimes useful to interpret on reverse polarity seismic sections The display gain is 8 This means that all of the amplitudes were scaled (i e multiplied) by a factor of 0 8 This value is determined from visually inspecting the data The display date is June 1990, i e the date when the seismic section was displayed

CDP FOLD DISPLAY

At the top of the seismic section is a graphical display of the CDP fold (see Appendix I) Near station 148, the fold exceeds 30, whereas on the ends of the line, the fold is less than 10

VELOCITY ANALYSES

Below the CDP fold display are several boxes displaying the results of the stacking velocity analyses Each analysis is displayed with the station location below In the analysis box on the left are the two-way times and on the right the corresponding root mean squared seismic velocity used to stack seismic reflection events

SURFACE PROFILE

Below the velocity analyses boxes is the surface elevation profile The elevation is displayed on both ends of the profile The solid line indicates the surface elevation The dashed line is the elevation of the unweathered zone determined from seismic refraction analysis

SEISMIC DATA DISPLAY

Immediately above the seismic reflection data display are station numbers On the left and right side of the data display is the two-way time scale (in seconds) Below each station is displayed one stacked seismic data trace, starting at time 0 0 second and ending at time 0 5 second Positive reflection events are displayed as dark-shaded positive peaks, with deflections to the right Negative reflection events are displayed unshaded with deflections to the left

DATA PROCESSING

The following is a brief description of the processing algorithms applied to the seismic data Some algorithms may be applied more than once with different parameters Subsequent applications are use to enhance different aspects of the data

DEMULTIPLEXING

In the field, seismic data were recorded by the EG&G ES-2420 seismic acquisition unit in multiplexed format Multiplexing is a process whereby multiple channels of data can be transmitted through a single channel without loss of information Multiplexed data samples are stored on tape in channel sequential order, whereas demultiplexed data samples are stored in time sequential order The seismic data traces are demultiplexed in the initial data processing stage

GAIN RECOVERY

The EG&G ES-2420 seismograph contains an automatic digital gain amplifier, which separately records the value of gain applied to each incoming sample A seismic wave undergoes sever amplitude attenuation as it travels through the earth and the digital gain amplifier compensates for this by attempting to restore seismic wave amplitudes to initial levels In the data processing stage, the different gains applied by the field instrument are equilibrated, to reproduce data traces that are consistent with respect to their true amplitudes

STATIC CORRECTIONS

The quality of the final seismic section is dependent upon the proper utilization of static corrections Static corrections are applied to seismic data to eliminate the effects of elevation, the weathering zone thickness and velocity variation The greater the variation in the surface elevation or near surface velocities, the more important static corrections become

DECONVOLUTION

Convolution is a mathematical process of passing one function through another to form a third function The appearance of a final seismic section is a result of the convolution of a seismic source signal with the earth's reflectivity characteristics An infinite bandwidth seismic signal convolved with the earth's reflectivity series would produce a very detailed cross-section of the earth's subsurface

A seismic source signal in the shape of a spike in the time domain has an infinite frequency bandwidth Unfortunately, seismic sources do not resemble perfect spikes Since the final seismic section is the result of filtering the reflectivity of the earth with the seismic source signal, an inverse filter can be designed (a deconvolution process) to recover the true reflectivity

A convolution with a "spike" (or broad-band frequency wavelet) will reproduce the original function The goal of deconvolution is to observe the spectrum of the seismic source pulse and design an inverse operator which reduces the pulse to a "spike" In completing this task, the processing geophysicist can apply the inverse operator to the reflected signals, thereby removing the effect of the source signal in them

CDP GATHERS/VELOCITY ANALYSIS

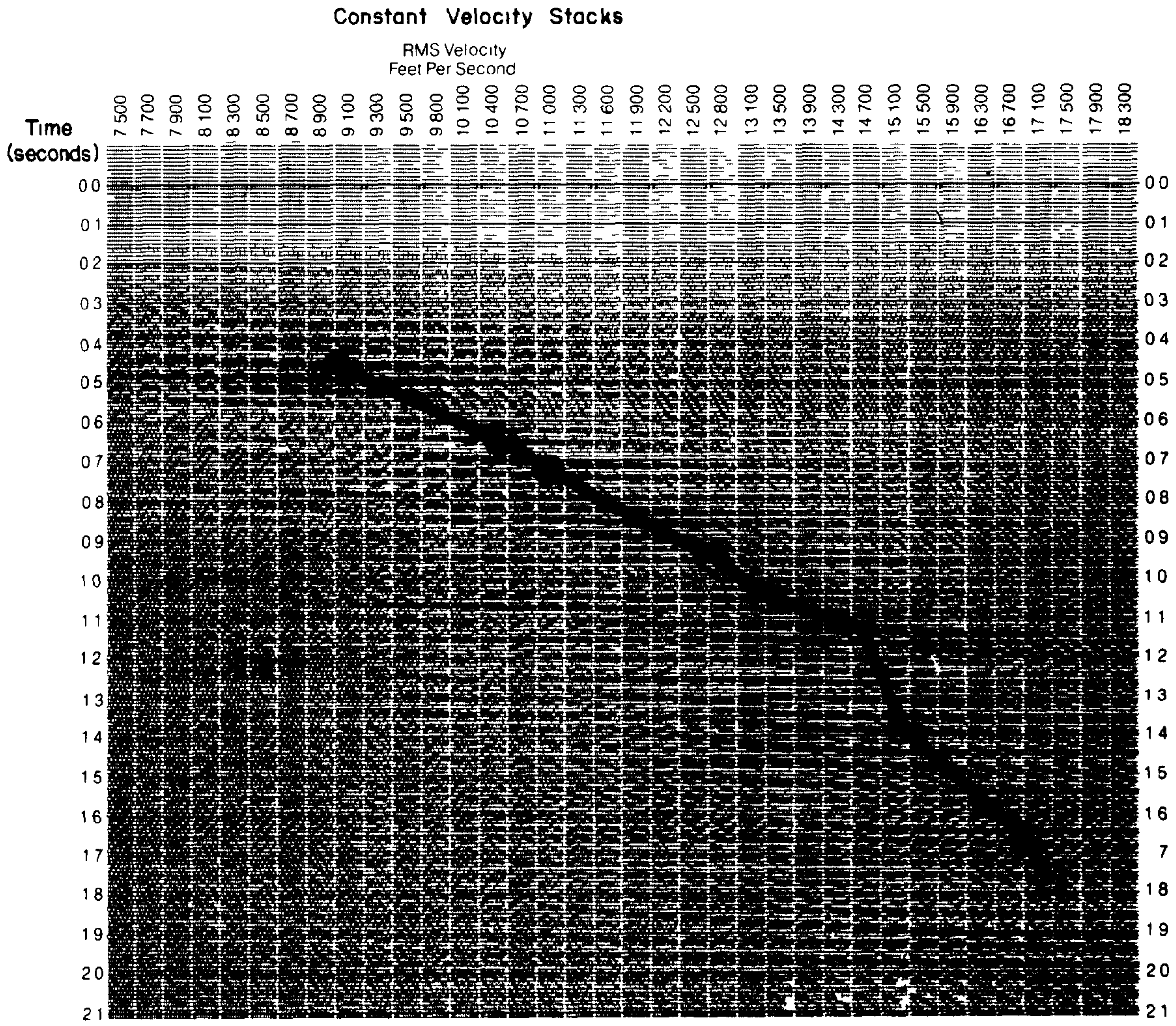
All data processing performed up to this stage has been based on sequential data for every shotpoint The data are now rearranged by CDP, gathering into CDP format, whereby all the traces common to one depth point are collected together

The difference in arrival times at two geophone locations for the same reflection is termed normal moveout This time difference can be utilized to estimate seismic velocities of different reflecting horizons After these interval velocities are assigned to the CDP gathered data, the resulting seismic section is examined for anomalous character that may indicate further velocity analysis is needed

Commonly constant velocity stacks are made to analyze the seismic velocities An example is shown in Figure A-4

STACKING

Stacking the seismic reflection data is one of the most important steps in the data processing sequence Seismic reflection data are recorded multi-fold to improve the S/N ratio For random noise (i e airplanes, raindrops, cars, etc) the improvement in the S/N ratio is equal to the square



Interpeted Velocity Analysis Function for Stacking CDP Data

Source Dobrin, 1976

DRAFTED AUGUST 1989

EBASCO SERVICES INCORPORATED
Prepared for
EG & G
ROCKY FLATS PLANT

FIGURE A-4

COMMON DEPTH POINT
VELOCITY ANALYSIS

root of n, where n is the CDP fold Random noise effects on the data are reduced and multiple reflections (multiples) are attenuated by the stacking process Properly stacked seismic data will result in a significant reduction of noise within the final seismic section

FINAL SECTION

The final seismic profile was displayed using a combination of variable area and wiggle trace The wiggle trace display enhances the wavelet shape, giving added insight to stratigraphic interpretation The variable area display emphasizes the wavelet amplitude, enhancing the lithologic identification

MIGRATION

Steeply dipping structures in the subsurface will be displaced from their true position on the seismic profile due to raypath imaging inconsistencies Migration processing can effectively remove the raypath inconsistencies and return a reflector to its true position on the final seismic section Migration processing becomes an increasingly important tool when there are steeply dipping structures present The Task 1 seismic modeling project utilized migration processing for structures with dips of seven to eight degrees The effect of the migration processing was noticeable when comparing the migrated and unmigrated seismic sections The Task 2 seismic sections indicate structural dips of approximately two to three degrees, and application of migration processing did not appreciably affect the subsurface structural characteristics of the seismic section However, migration improves the S/N ratio by approximately 6 decibles (db)

COMPLEX ATTRIBUTE ANALYSIS

A seismic wave involves moving particles of matter out of their equilibrium positions and thus involves kinetic energy Hence, the conventional seismic trace may be thought of as a measure of kinetic energy The particle motion is resisted by an elastic restoring force so that energy becomes stored as potential energy As a particle moves in response to the passage of a seismic wave, the energy transfers back and forth between kinetic and potential forms The quadrature trace may be thought of as a measure of potential energy (Taner et al , 1979)

The quadrature (or complex) trace can be calculated from the conventional seismic trace From the quadrature trace several attributes can be calculated These are

1) Reflection strength
2) Instantaneous phase
3) Instantaneous frequency

The reflection strength is a measure of the total amplitude of the seismic trace independent of peaks and troughs The reflection strength is also a measure of the reflection character It is sometimes an aid, for example, in distinguishing between reflections from massive reflectors and those which are interference composites Unconformities often show changes in reflection strength character as the subcropping beds change Seismic sequence boundaries tend to have fairly large reflection strengths

The instantaneous phase is a quantity which is independent of reflection strength Phase emphasizes the continuity of events Weak coherent events are thus brought out Phase displays are especially effective in showing pinchouts, angularities, and the interference of events with different dip attitudes

The time derivative of the instantaneous phase is called instantaneous frequency The instantaneous frequency can vary quite rapidly Sometimes it is useful to smooth frequency measurements with a weighted function Petroleum exploration applications have found instantaneous frequency to be a good indicator of condensate reservoirs This is the first use of instantaneous frequency to shallow applications Seismic reflection events from interbedded fluvial deposits have a high instantaneous frequency response (Irons and Lewis, 1990) The instantaneous frequency plots were used as an auxiliary interpretation tool, however, the interpretation relied mostly on the final stacked profiles

DANIEL GEOPHYSICAL PROCESSING REPORT

INTRODUCTION

This project was comprised of high resolution digital seismic processing of newly acquired shallow, CDP seismic reflection data in the Rocky Flats Plant Site Area

This report encompasses the derived basic processing sequence of the above pilot study, but does not include the optional steps being currently formulated or run The intent of the report is to briefly outline and describe the processing steps instituted and other techniques tested but not implemented

PROCESSING SEQUENCE DESCRIPTION

The processing sequence was derived from tests conducted on Lines T2, 2, and 3 of the 15 lines that were shot The initial tests were done on Line T2 through Step 17 However, refraction statics were not run on T2 because of the shooting geometry and resultant deficiency in reciprocal travel paths Because of the proximity of a 150 feet (ft) well to Line 2, it became the pilot line for future tests with the exception of migration tests on Line 3 In all cases, except for refractions statics not being applied on Line T2, the processing steps were the same on all 15 lines

Where applicable, brief comments of additional testing in the steps as shown in the Processing Flow Diagram (see Figure 3-1) and Processing Sequence as shown on a seismic profile side label are as follows

1) DEMULTIPLEX

Comments 9 track, multiplexed, SEG D format

0 25 ms sample rate

96 data channels

4 auxiliary channels flagged as data channels

Flagging 4 auxiliary channels as data channels should be avoided in future programs since they had to be reset to auxiliary channels in the processing center

2) RECORDING GAIN REMOVAL

3) GEOMETRY DEFINITION APPLICATION

Comments Line T2 was recorded with 3 ft group intervals and Lines 1, 2, 3, 4, and 5 were shot with 2 ft group intervals

4) TRACE EDITING, BULK TIME SHIFTS

Comments Differences in elapsed times between when the shot was fired and recorded occurred on these lines

There was no delay on Line T2, but Lines 1, 2, 3, and 4 had to be bulk shifted by -50 ms, problems were corrected on individual shots for Line 5

5) SURFACE-CONSISTENT DECONVOLUTION

Comments Besides the parameter testing done on surface-consistent decon, conventional deconvolution testing were analyzed on Line T2 These tests were run pre-stack with 3, 6, 12, 24 and 48 ms GAPS and 50 and 150 ms operator lengths and then stacked The auto correlations were obtained on the stacked traces The predictive DCON with a 50 ms operator and 6 ms GAP looked the cleanest, but no significant difference was observed between the conventional decon and surface-consistent decon Therefore, because of the robust nature of surface-consistent decon, and conventional decon could be applied in a latter stage (Step 14), the former was chosen

6) GAIN RECOVERY

Comments Conventional spherical divergence corrections and inelastic attenuation corrections were tested on the data, but a short AGC operator was more effective in obtaining high frequencies

7) SPECTRAL BALANCING

Comments Power spectrums and F-K analyses of the demux records and amplitude spectra displays from the surface-consistent decon indicated that the data was 25 db's down at 60 and 540 Hz Therefore, the data were approximately whitened between this range before noise reduction was run on the shots

8) LOCALIZED SLANT STACK
NOISE REDUCTION ON SHOTS

Comments Noise reduction with velocity filter and localized slant stacks (NORLOC) were tested on various lines with the NORLOC routine having a significant impact on suppressing air waves, ground and air traffic noise, and also noise from a core drill rig

9) CDP GATHERS

10) DATUM STATICS APPLICATION

11) BRUTE VELOCITY ANALYSES

12) SURFACE-CONSISTENT AUTOMATIC STATICS

13) FINAL VELOCITY ANALYSES

14) PREDICTIVE DECONVOLUTION

Comments The conventional decon tests as described in Step 5 were run in Step 14 The results were similar and had a tendency to sharpen the wavelets

15) NORMAL MOVEOUT CORRECTION

16) POST NMO MUTE

17) REMOVE DATUM STATICS

18) DANIEL GRM REFRACTION STATICS APPLICATION

19) SURFACE-CONSISTENT AUTOMATIC STATICS

20) SPATIAL FILTER ON SHOTS (X-T NOISE REDUCTION)

Comments 15% and 25% addback of the enhanced signal traces (60-600 Hz) were tested and then the data was stacked 25% addback had the most significant improvement in reduction of noise

21) CDP-CONSISTENT RESIDUAL STATICS

Comments One long gate, one deep gate, one shallow gate, and a combination of shallow and deep gates were tested and stacked The cascaded runs gave better results than the other three

22) CDP STACK

23) TIME-VARIANT STACKING

Comments Five post stack scaling tests were compared - 50 ms and 100 ms AGC, one full trace balance, and two 3 gate balance tests with 0-40 ms, 40-70 ms and 70-450 ms being chosen

24) SPATIAL FILTER NOISE REDUCTION

Comments Similar testing as in Step 20 was done post-stack with the same results A two-dimensional F-K noise reduction filter was also tested with less desirable appearance

25) TIME-VARIANT FILTER

Comments From filter tests a 60/80-300/360 Hz and a 60/80-440/500 Hz filters were picked Four separate film displays with these filters will be plotted with normal and reverse polarities at 50 inches/sec , 10 traces/inch

For the migrated sections

24) FINITE DIFFERENCE MIGRATION

Comments The following parameters were tested - (NFPS) number filter points in migration spatial filter 15, 11, 7, and 5

(MPLEX) increase spatial sampling 1, 2, and 4

(TAU) migration layers 2, 5, and 10 migration velocities 90 and 100% RMS stacking velocities It was decided that 90% RMS stacking velocities, MPLEX=4, TAU=2, NFPS=5 achieved the best results with the exception of MPLEX=2 on Line T2

25) SPATIAL FILTER NOISE REDUCTION

26) TIME-VARIANT FILTER

Comments One of the final filters will be chosen Two separate film displays with this filter will be plotted with normal and reverse polarities at 50 inches/sec , 10 traces/inches

SUMMARY

Datum Statics Application (Step 10) could be replaced with Refraction Statics Application or run simultaneously and compared at the initial stack stage for a best approach There was not any appreciable difference between either method on this data set The current order was more of a processing convenience rather than a technical necessity The most dramatic or important step was NORLOC (Step 8) which contributed significantly in suppression of noise The derived processing sequence resulted in a progressional improvement in the S/N ratio of the data from step to step

REFERENCE

Irons L A and B Lewis 1990 Shallow High-Resolution Seismic Reflection Investigation on a Hazardous Waste Site Proceedings of the Fourth National Outdoor Action Conference on Aquifer Restoration, Ground Water Monitoring, and Geophysical Methods Number 2 Presented by the Association of Ground Water Scientists and Engineers, Division of NWWA pp 1129-1142

SEG (Society of Exploration Geophysics) Technical Standards Committee 1980 Digital Tape Standards

Taner, M T , F Koehler, and R E Sheriff 1979 Complex Trace Analysis Geophysics, 44, 1041-1063

GLOSSARY

A selection of relevant geophysical terms extracted from
Encyclopedic Dictionary of Exploration Geophysics (Sheriff, 1984),
Applied Geophysics (Telford et al , 1976),
Geophysical Prospecting (Dobrin, 1976, Dobrin and Savit, 1988)

ACCELEROMETER -	A geophone whose output is proportional to the acceleration of earth particles For example, a moving coil geophone, with velocity response proportional to frequency (as may be the case below the natural frequency) operates as an accelerometer
ACOUSTIC - IMPEDANCE	Seismic velocity multiplied by density Reflection coefficient at normal incidence depends on changes in acoustic impedance
ACOUSTIC LOGGING -	A borehole logging survey which will display any of several aspects of seismic-wave propagation, i e , a sonic, amplitude, character or 3D-log
AIR WAVE -	Energy from the shot which travels in the air at the velocity of sound V = 1051 + 1 1F ft/s, where F = Fahrenheit temperature, or V = 331 5 + 0 607C m/s, where C = Celsius temperature
ALIAS -	Data in sampled form have an ambiguity where there are fewer than two samples per cycle This creates a situation where an input signal at one frequency appears to have another frequency at the output of the system Half of the frequency of sampling is called the folding or Nyquist frequency, f_N, and a frequency larger than this, $f_N + Y$, appears to have the smaller frequency f_N-Y To avoid this ambiguity, frequencies above the Nyquist frequency must be removed by an anti-alias filter before the sampling Otherwise the system will react as if the spectral characteristics were folded back at the Nyquist frequency Thus, for a system sampled over 4 msec, or 250 times per second, the Nyquist frequency is 125 cps, if, for example, 50 cps is within the pass band, then 200 cps will also be passed if an anti-alias filter is not used, appearing upon output to have a 50 cps frequency The pass bands obtained by folding about the Nyquist frequency are also called "alias bands," "side lobes," and "secondary lobes " Aliasing is an inherent property of all sampling systems and applies to digital seismic recording and also to the sampling which is done by the separate elements of geophone and shotpoint arrays

ANALOG - (1) A continuous physical variable (such as voltage or rotation) which bears a direct relationship (usually linear) to another variable (such as earth motion) so that one is proportional to the other (2) Continuous, as opposed to discrete or digital

ANOMALY - A deviation from uniformity in physical properties, often of exploration interest For example, a travel time anomaly, Bouguer anomaly, free-air anomaly

APPARENT VELOCITY - (1) The phase velocity which a wavefront appears to have along a line of geophones (2) The inverse of the slope of a time-distance curve

ATTENUATION - A reduction in amplitude or energy caused by the physical characteristics of the transmitting media or system Usually includes geometric effects such as the decrease in amplitude of a wave with increasing distance from a source Also used for instrumental reduction effects such as might be produced by passage through a filter

AUTOMATIC GAIN CONTROL (AGC) - A system in which the output amplitude is used for automatic control of the gain of a seismic amplifier, usually individual for each channel, although multi-channel devices are sometimes used

BEDROCK - Any solid rock, such as may be exposed at the surface of the earth or overlain by unconsolidated material

BODY WAVES - P-waves and S-waves, which travel through the body of a medium, as opposed to surface waves

CABLE - The assembly of electrical conductors used to connect the geophone groups to the recording instrument

CAPACITANCE - The ratio of charge (Q in coulombs) on a capacitor to the potential across it (V in volts) is the capacitance (C in farads)

$$C = Q/V$$

CHANNEL - (1) A single series of interconnected devices through which geophysical data can flow from sources to recorder Most seismic systems are 24 channel, allowing the simultaneous recording of energy from 24 groups of geophones (2) A localized elongated geological feature resulting from present or past drainage or water action, often presents a weathering problems (3) An allocated portion of the radio-frequency spectrum

CHANNEL WAVE - An elastic wave propagated in a layer of lower velocity than those on either side of it Energy is largely prevented from escaping from the channel because of repeated total reflection at the channel boundaries or because rays which tend to escape are bent back toward the channel by the increasing velocity away from it in either direction

CHARACTER - (1) The recognizable aspect of a seismic event, usually in the waveform, which distinguishes it from other events Usually a frequency or phasing effect, often not defined precisely and hence dependent upon subjective judgment (2) A single letter, numeral, or special symbol in a processing system

COMMON DEPTH POINT (CDP) - The situation where the same portion of subsurface produces reflections at different offset distances on several profiles

COMPRESSIONAL WAVE - An elastic body wave in which particle motion is in the direction of propagation (Same as P-waves, longitudinal wave, dilation wave)

CONVERTED WAVE - A wave which is converted from longitudinal to transverse, or vice versa, upon reflection or refraction at oblique incidence from an interface

CRITICAL ANGLE - Angle of incidence, q_c, for which the refracted ray grazes the surface of contact between two media (of velocities V_1 and V_2)

$$\sin q_c = V_1/V_2$$

CRITICAL DISTANCE - (1) The offset at which the reflection time equals the refraction time, that is, the offset for which the reflection occurs at the critical angle (see Sheriff, 1984 p 45) (2) Sometimes incorrectly used for crossover distance, the offset at which a refracted event becomes the first break

CROSSFEED - Interference resulting from the unintentional pickup of information or noise on one channel from another channel Also crosstalk

CROSS-HOLE METHOD - Technique for measuring in situ compressional (p) and/or shear (s) wave velocities by recording transit times from a source within one borehole to receivers at the same elevation in one or more other boreholes Sources may be explosive or directional to enhance either P- or S-wave generation

CROSS SECTION - A plot of seismic events

DATUM - (1) The arbitrary reference level to which measurements are corrected (2) The surface from which seismic reflection times or depths are counted, corrections having been made for local topographic and/or weathering variations (3) The reference level for elevation measurements, often sea level

DELAY TIME - (1) In refraction work, the additional time required for a wave to follow a trajectory to and along a buried marker over that which would have been required to follow the same marker considered hypothetically to be at the ground surface or at a reference level Normally, delay time exists separately under a source and under a detector, and is dependent upon the depth of the marker at wave incidence and emergence points Shot delay time plus geophone delay time equals intercept time (See Dobrin, 1988 p 472) (2) Delay produced by a filter

DIELECTRIC CONSTANT - A measure of the capacity of a material to store charge when an electric field is applied It is the dimensionless ratio of the capacitivity (or permittivity, the ratio of the electrical displacement to the electric field strength) of the material to that of free space

DIFFRACTION - (1) Scattered energy which emanates from an abrupt irregularity of rock type, particularly common where faults cut reflecting interfaces The diffracted energy shows greater curvature than a reflection (except in certain cases where there are buried foci), although not necessarily as much as the curve of maximum convexity It frequently blends with a reflection and obscures the fault location or becomes confused with dip (2) Interference produced by scattering at edges (3) The phenomenon by which energy is transmitted laterally along a wave crest When a portion of a wave train is interrupted by a barrier, diffraction allows waves to propagate into the region of the barrier's geometric shadow

DIGITAL - Representation of quantities in discrete units A digital system is one in which the information is contained and manipulated as a series of discrete numbers as opposed to an analog system, in which the information is represented by a continuous flow of the quantity constituting the signal

DOWN-HOLE METHOD -	Technique for measurement of in situ compressional and shear wave velocities utilizing a seismic source at ground surface and a clamped triaxial geophone at depth in a borehole Shear wave energy is often enhanced by use of directional sources such as striking the ends of a weighted plank
END LINE -	Shotpoints that are shot near the end of the spread
FIRST BREAK -	The first recorded signal attributable to seismic wave travel from a known source First breaks on reflection records are used for information about the weathering Refraction work is based principally on the first breaks, although secondary (later) refraction arrivals are also used Also first arrival
FOLD -	The multiplicity of common-midpoint data Where the midpoint is the same for 12 offset distances, e g , the stack is referred to as "12-fold"
FREQUENCY DOMAIN -	A representation in which frequency is the independent variable, the Fourier transform variable when transforming from time
GAIN -	An increase (or change) in signal amplitude (or power) from one point in a circuit or system to another, often from system input to output
GALVANOMETER -	A part of a seismic camera consisting of a coil suspended in a constant magnetic field The coil rotates through an angle proportional to the electrical current flowing through the coil A small mirror on the coil reflects a light beam, which exhibits a visual record of the galvanometer rotation
GEOPHONE -	The instrument used to convert seismic energy into electrical voltage Same as seismometer
GEOPHONE STATION -	Point of location of a geophone on a spread, expressed in engineering notation as 1+75 taken from 0+00 at the beginning of the line

GROUP VELOCITY - The velocity with which most of the energy in a wave train travels In dispersive media where velocity varies with frequency, the wave train changes shape as it progresses so that individual wave crests appear to travel at a different velocity (the phase velocity) than the overall energy as approximately enclosed by the envelope of the wave train The velocity of the envelope is the group velocity Same as dispersion

HYDROPHONE - (Pressure detector) A detector which is sensitive to variations in pressure, as opposed to a geophone which is sensitive to particle motion Used when the detector can be placed below a few feet of water, as in marine or marsh or as a well seismometer The frequency response of the hydrophone depends on its depth beneath the surface

IMPEDANCE - The apparent resistance to the flow of alternating current, analogous to resistance in a dc circuit Impedance is (in general) complex, of magnitude Z with a phase angle g These can be expressed in terms of resistance R (in ohms), inductive reactance $X_L = 2pL$, and capacitive reactance $X_c = 1/2pnC$

$$Z = [R^2 + (X_L - X_C)^2]^{1/2}$$
$$g = \tan^{-1}[(X_L - X_C)/R]$$

Z is in ohms when frequency n is in hertz, L is inductance in henrys, and C is capacitance in farads

IN-LINE OFFSET - A spread which is shot from a shotpoint which is separated (offset) from the nearest active point on the spread by an appreciable distance (more than a few hundred feet) along the line of spread

INPHASE - Electrical signal with the same phase angle as that of the exciting signal or comparison signal

LEAD - An electrical conductor for connecting electrical devices Geophones are connected to cables at the takeouts via leads on the geophones

LINE - A series of profiles shot in line

LOVE WAVE - A surface seismic channel wave associated with a surface layer which has rigidity, characterized by horizontal motion perpendicular to the direction of propagation with no vertical motion

LOW-VELOCITY LAYER - A near-surface belt of very low-velocity material often abbreviated LVL, also called weathering

MAGNETIC PERMEABILITY - The ratio of the magnetic induction B to the inducing field strength H denoted by the symbol m

$$m = B/moH$$

mo is the permeability of free space = 4p10[7] weber/ampere meter or (henrys/meter) in SI system, and 1 gauss/oersted in the cgs system, so that the permeability m is dimensionless The quantity mmo is sometimes considered the permeability (especially in the cgs system)

MIS-TIE - (1) The time difference obtained on carrying a reflection, phantom, or some other measured quantity around a loop, or the difference of the values at identical points on intersecting lines or loops (2) In refraction shooting, the time difference from reversed profiles which gives erroneous depth and dip calculations

MULTIPLE - Seismic energy which has been reflected more than once Same as long-path multiple, short path multiple, peg-leg multiple, and ghost

MULTIPLEX - A process which permits transmitting several channels of information over a single channel without crossfeed Usually different input channels are sampled in sequence at regular intervals and the samples are fed into a single output channel, digital seismic tapes are multiplexed in this way Multiplexing can also be done by using different carrier frequencies for different information channels and in other ways

NOISE - (1) Any undesired signal, a disturbance which does not represent any part of a message from a specified source (2) Sometimes restricted to energy which is random (3) Seismic energy which is not resolvable as reflections In this sense noise includes microseisms, shot-generated noise, tape-modulation noise, harmonic distortions, etc Sometimes divided into coherent noise (including non-reflection coherent events) and random noise (including wind noise, instrument noise, and all other energy which is non-coherent) To the extent that noise is random, it can be attenuated by a factor of n by compositing n signals from independent measurements (4) Sometimes restricted to seismic energy not derived from the shot explosion (5) Disturbances in observed data due to more or less random inhomogeneities in surface and near surface material

NOISE SURVEY - A mapping of ambient, continuous seismic noise levels within a given frequency band As some geothermal reservoirs are a source of short-period seismic energy, this technique is a useful tool for detecting such reservoirs Also called ground noise survey

OBSERVER - The geophysicist in charge of recording and overall field operations on a seismic crew

ON-LINE - Shotpoints that are shot at any point on a spread other than at the ends of the spread

OSCILLOGRAPH - An instrument that renders visible a curve representing the time variations of electric phenomena

OSCILLOSCOPE - A type of oscillograph that visually displays an electrical wave on the screen of a cathode ray tube type

PERMITTIVITY - Capacitivity (q v) of a three-dimensional material, such as a dielectric Relative permittivity is the dimensionless ratio of the permittivity of a material to that of free space, it is also called the dielectric constant

PHASE VELOCITY - The velocity with which any given phase (such as a trough or a wave of single frequency) travels, may differ from group velocity because of dispersion

PLANT - The manner in which a geophone is placed on or in the earth, the coupling to the ground

PROFILE - The series of measurements made from several shotpoints into a recording spread from which a seismic data cross section or profile can be constructed

PROFILING - A geophysical survey in which the measuring system is moved about an area (often along a line) with the objective of determining how measurements vary with location Specifically, a resistivity, IP, or electromagnetic field method wherein a fixed electrode or antenna array is moved progressively along a traverse to create a horizontal profile of the apparent resistivity

RADAR - A system in which short electromagnetic waves are transmitted and the energy scattered back by reflecting objects is detected Acronym for "radio detection and ranging " Ships use radar to help "see" other ships, buoys, shorelines, etc Beacons sometimes provide distinctive targets Radar is used in aircraft navigation (see Doppler-radar), in positioning, and in remote sensing

RADIO FREQUENCY - A frequency above 3kHz Radio frequencies are subdivided into bands

RAYLEIGH WAVE - A seismic wave propagated along the free surface of a semi-infinite medium The particle motion near the surface is elliptical and retrograde, in the vertical plane containing the direction of propagation

RAYPATH - A line everywhere perpendicular to wavefronts (in isotropic media) The path which a seismic wave takes

REFLECTION SURVEY - A survey of geologic structure using measurements made of arrival time of events attributed to seismic waves which have been reflected from interfaces where the acoustic impedance changes

RESOLUTION - The ability to separate two features which are very close together

SEISMIC AMPLIFIER - An electronic device used to increase the electrical amplitude of a seismic signal (See geophone)

SEISMIC CAMERA - A recording oscillograph used to produce a visible pattern of electrical signals to make a seismic record

SEISMIC VELOCITY - The rate of propagation of a seismic wave through a medium

SEISMOGRAM - A seismic record

SHEAR WAVE - A body wave in which the particle motion is perpendicular to the direction of propagation (Same as S-wave, equivoluminal, transverse wave)

SHOOTER - The qualified, licensed individual (powderman) in charge of all shotpoint operations and explosives handling on a seismic crew

SHOT DEPTH -	The distance down the hole from the surface to the explosive charge, often measured with loading poles With small charges the shot depth is measured to the center or bottom of the charge, but with large charges the distances to both the top and bottom of the column of explosives are usually given
SHOT INSTANT -	(Time Break (TB), Zero Time) - The time at which a shot is detonated
SHOTPOINT -	Point of location of the energy source used in generating a particular seismogram Expressed either sequentially for a line (i e SP 3) or in engineering notation (i e SP 3+00)
SIGNAL ENHANCEMENT -	A hardware development utilized in seismographs and resistivity systems to improve signal-to-noise ratio by real-time adding (stacking) successive waveforms from the same source point and thereby discriminating against random noise
SIGNAL-TO-NOISE RATIO SOUNDING-	The energy (or sometimes amplitude) divided by all remaining energy (noise) at the time, abbreviated S/N
SOUNDING -	Measuring a property as a function of depth, a depth probe or expander Especially a series of electrical resistivity readings made with successively greater electrode spacing while maintaining one point in the array fixed, thus giving resistivity-versus-depth information (assuming horizontal layering), electric drilling, probing, VES (vertical electric sounding)
SPREAD -	The layout of geophone groups from which data from a single shot are recorded simultaneously
STONELEY WAVE -	A type of seismic wave propagated along an interface
SURFACE WAVE -	Energy which travels along or near the surface (ground roll)
SYNTHETIC SEISMOGRAM -	An Artificial seismic record manufactured from velocity log data used to compare with and actual seismogram to aid in identify events or in predicting how stratigraphic variations might affect seismic record

Often constructed from sonic log data alone although density data may also be incorporated

TAKEOUT - A connection point to a multiconductor cable where geophones can be connected

TIME BREAK (TB)- The mark on a seismic record which indicates the shot instant or the time at which the seismic wave was generated

TIME DOMAIN - 1 Expression of a variable as a function of time, as opposed to its expression as a function of frequency (frequency domain) Processing can be done using time as the variable, i e , "in the time domain" For example, convolving involves taking values at successive time intervals, multiplying by appropriate constants, and recombining, this is equivalent to filtering through frequency-selective circuitry It is also equivalent to Fourier transforming, multiplying the amplitude spectra, and adding the phase spectra ("in the frequency domain"), and then inverse-Fourier transforming

2 Time-domain induced polarization is called the pulse method (q v)

TOMOGRAPHY - The reconstruction of an object from a set of its projections Tomographic techniques are utilized in medical physics as well as in cross-borehole electromagnetic and seismic transmission surveys

TRACE - A record of one seismic channel This channel may contain one or more geophones A trace is made by a galvanometer

UPHOLE METHOD- Also called the Meissner technique, a method of reconstructing wave front diagrams by shooting at several depths and recording on a full surface spread of geophones Derived wavefront diagrams yield a true picture of wavepaths and, therefore, layering in the subsurface

WAVE TRAIN - (1) The sum of a series of propagating wave fronts emanating from a single source (2) The complex wave form observed in a seismogram obtained from an explosive source

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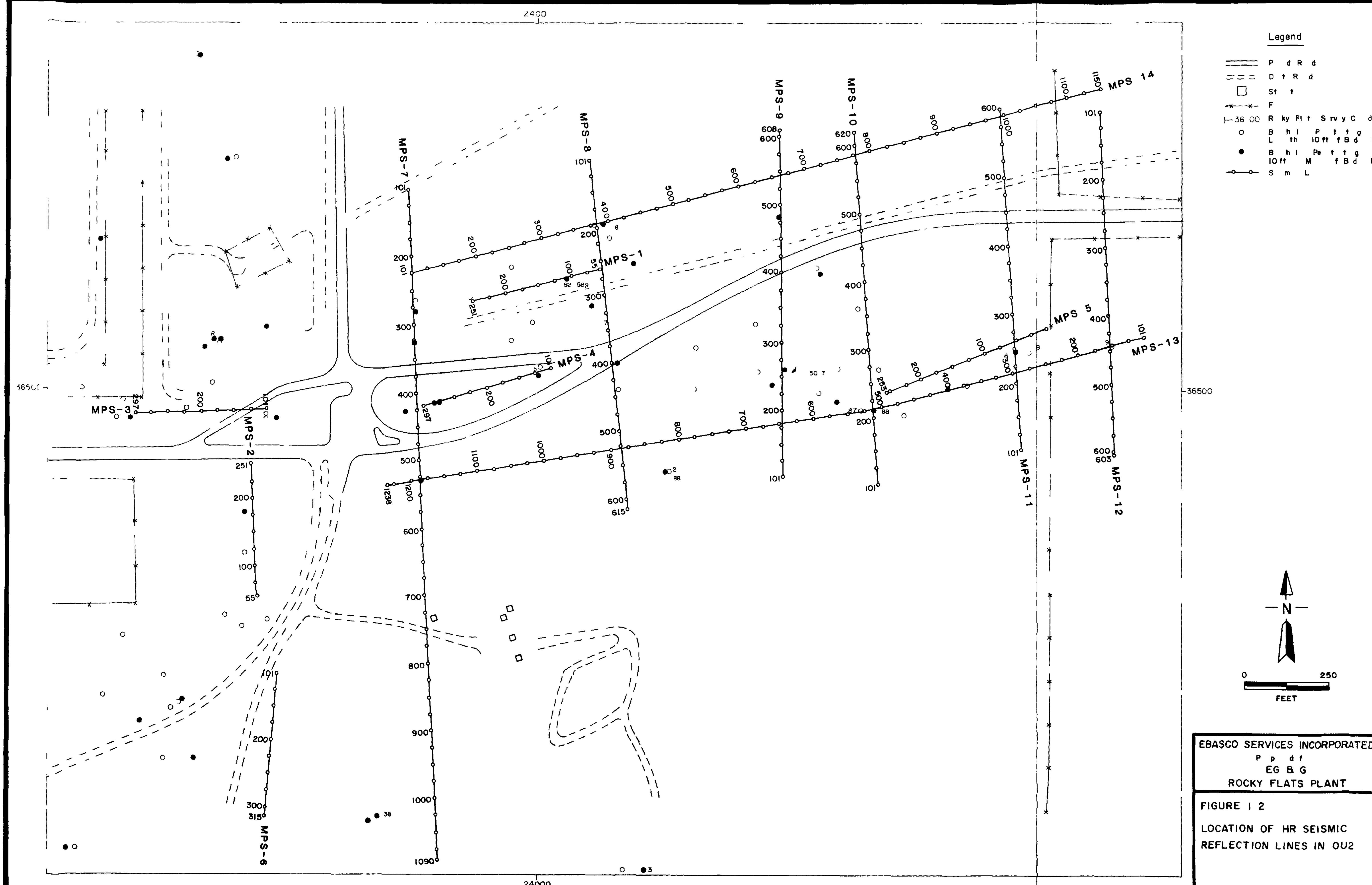

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ROCKY FLATS PLANT

FIGURE I 2

LOCATION OF HR SEISMIC REFLECTION LINES IN OU2

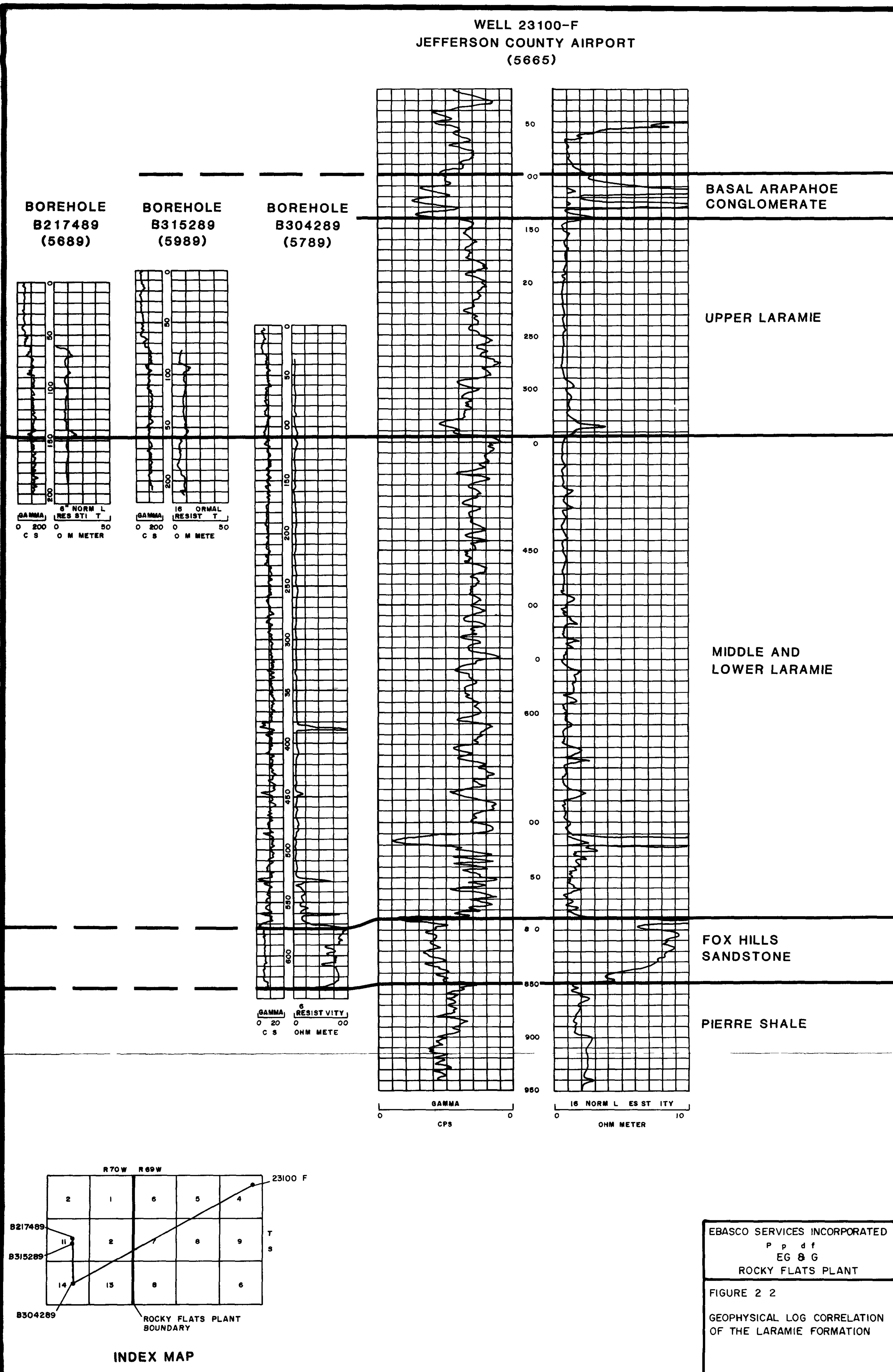

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FIGURE 2 2

GEOPHYSICAL LOG CORRELATION
OF THE LARAMIE FORMATION

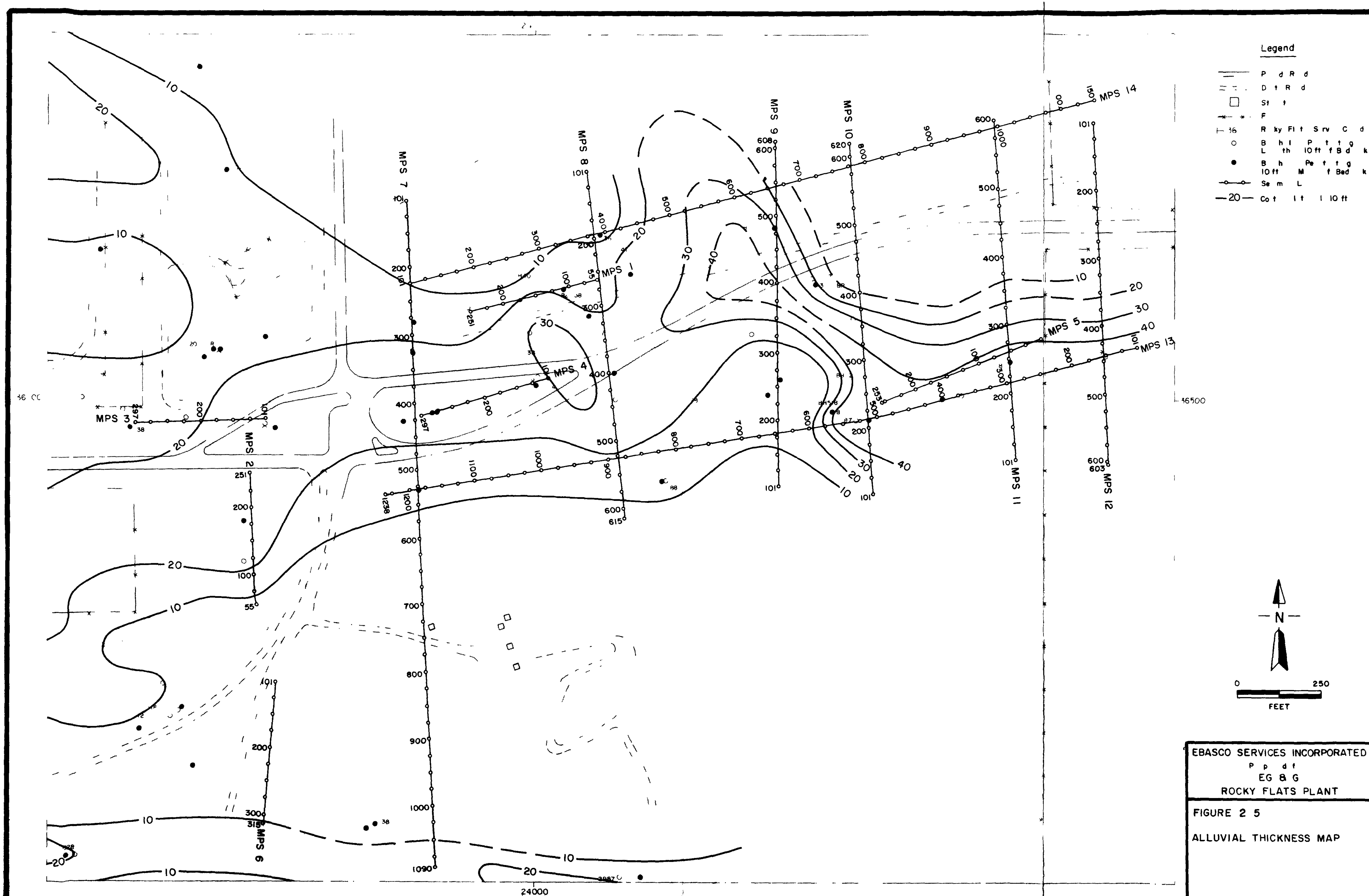

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FIGURE 2 5

ALLUVIAL THICKNESS MAP

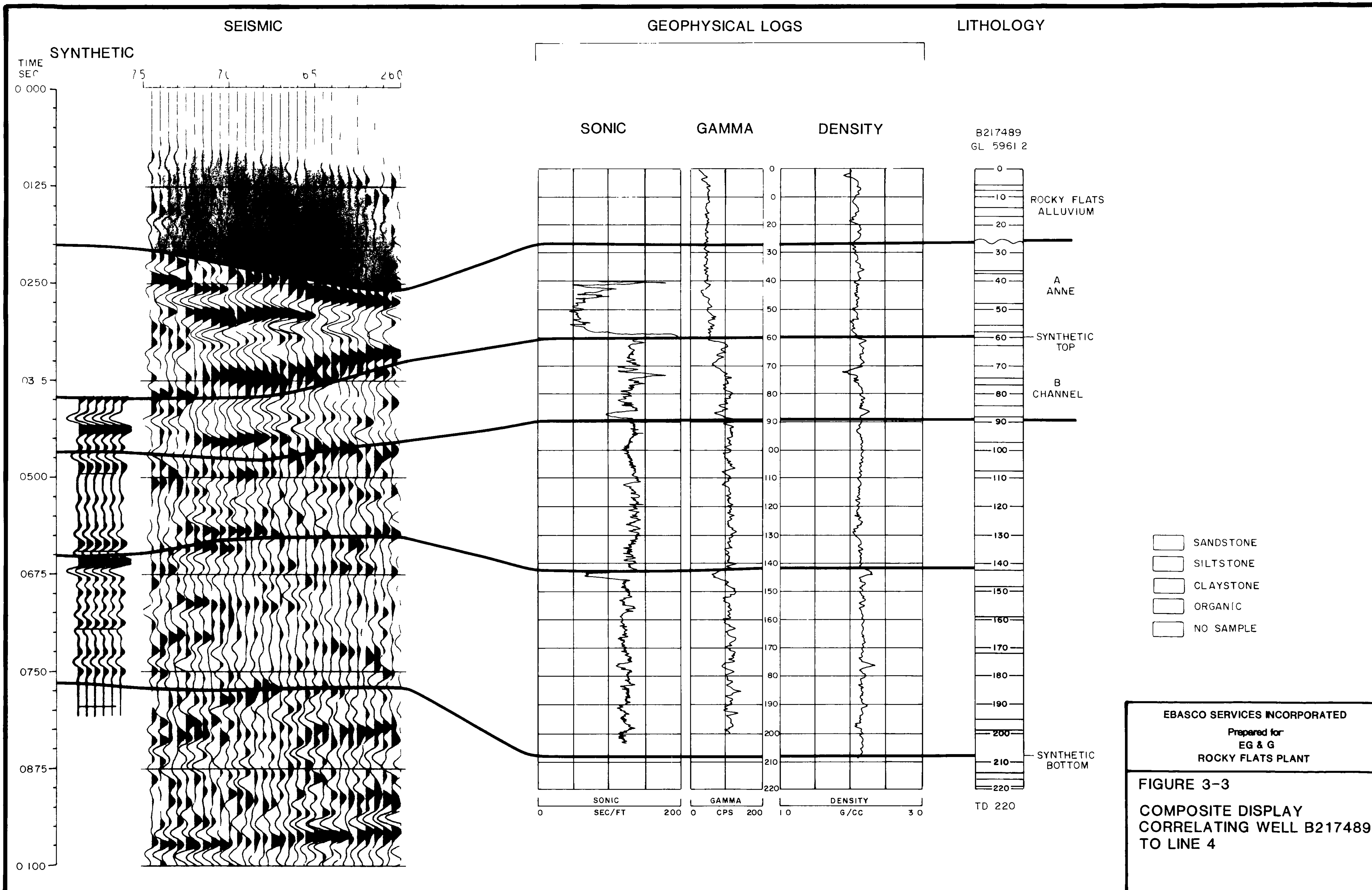

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FIGURE 3-3

COMPOSITE DISPLAY CORRELATING WELL B217489 TO LINE 4

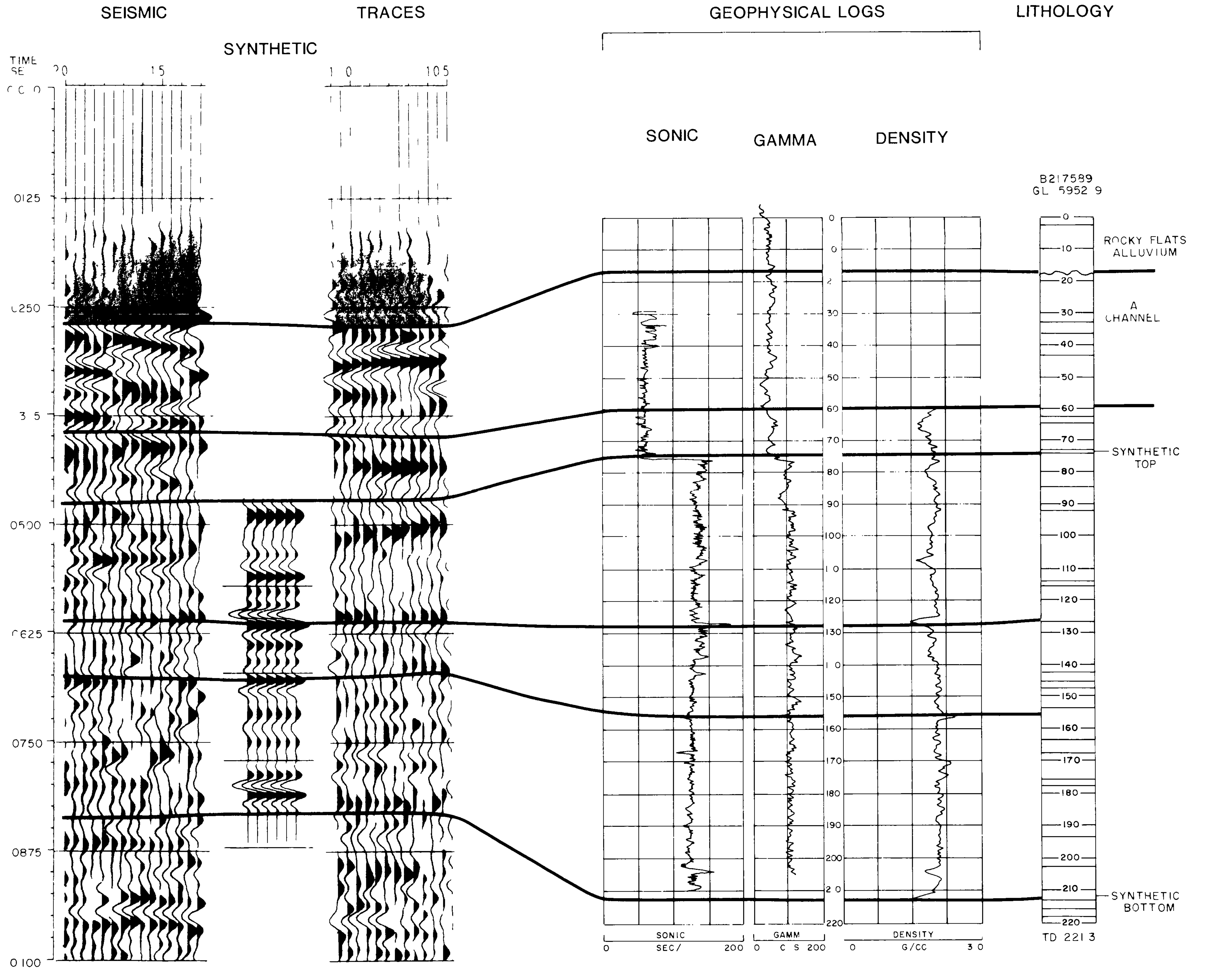

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FIGURE 3-2
COMPOSITE DISPLAY
CORRELATING WELL B217589
TO LINE 1

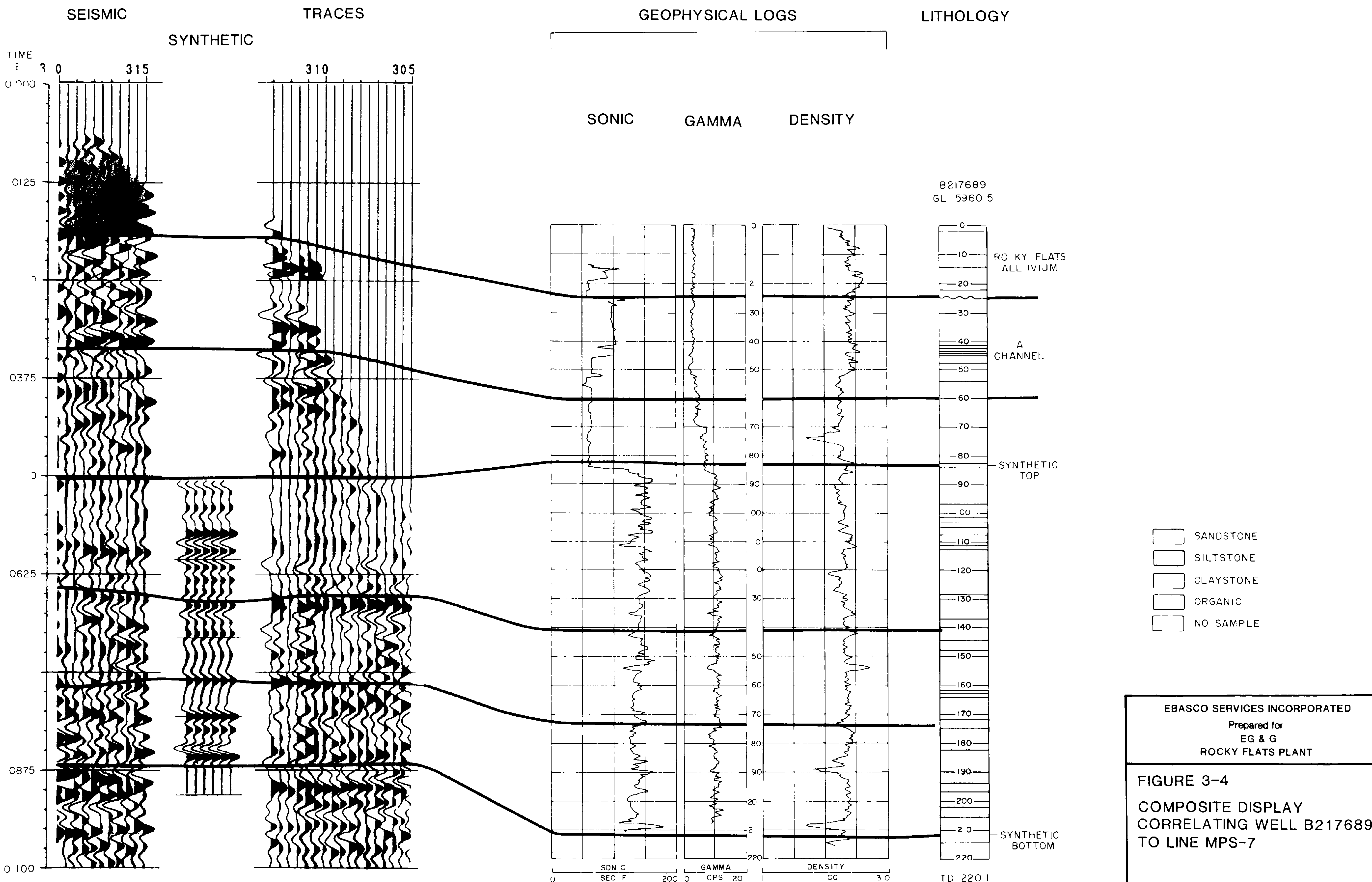

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FIGURE 3-4
COMPOSITE DISPLAY
CORRELATING WELL B217689
TO LINE MPS-7

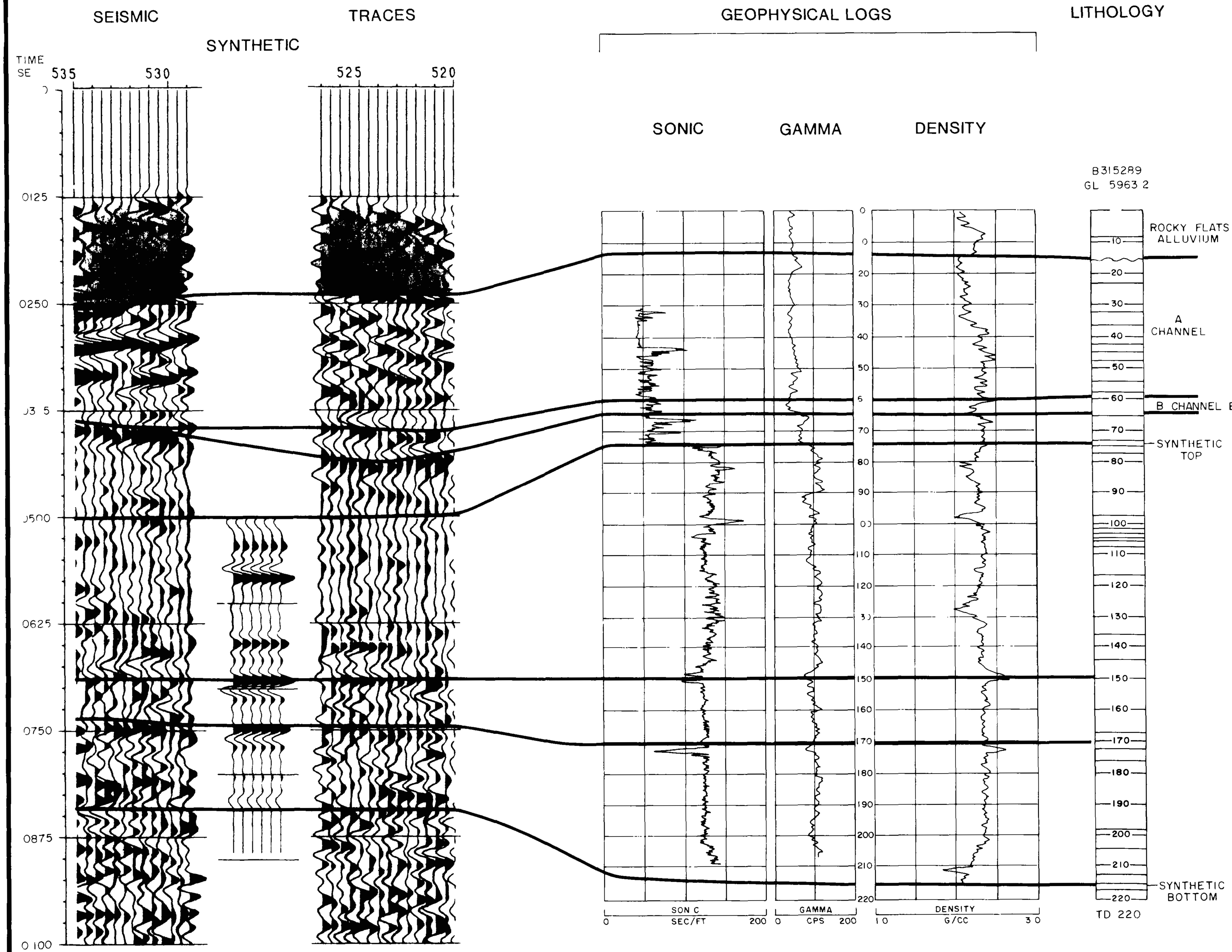

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FIGURE 3-5

COMPOSITE DISPLAY CORRELATING WELL B315289 TO LINE MPS-7

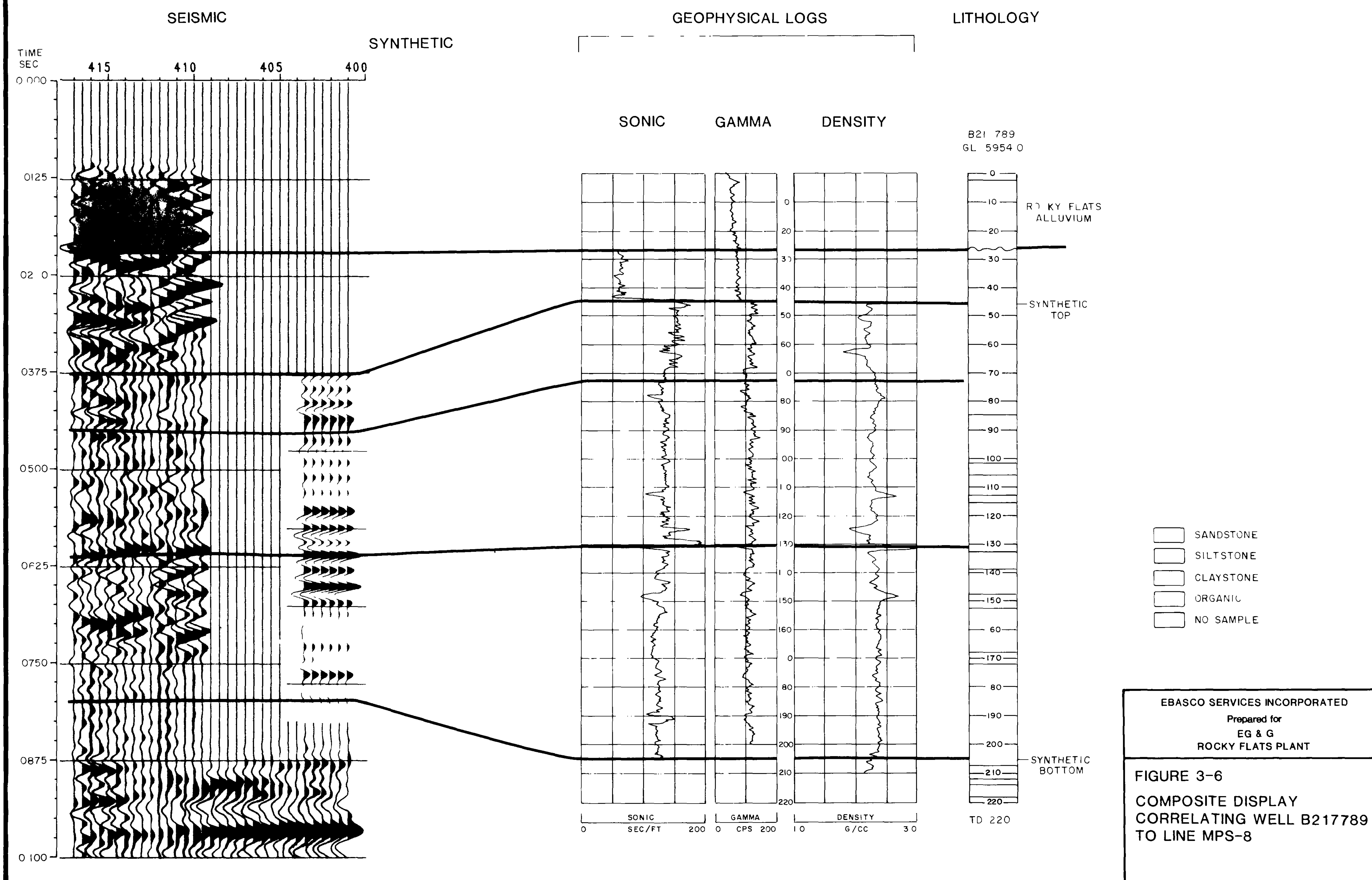

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FIGURE 3-6
COMPOSITE DISPLAY CORRELATING WELL B217789 TO LINE MPS-8

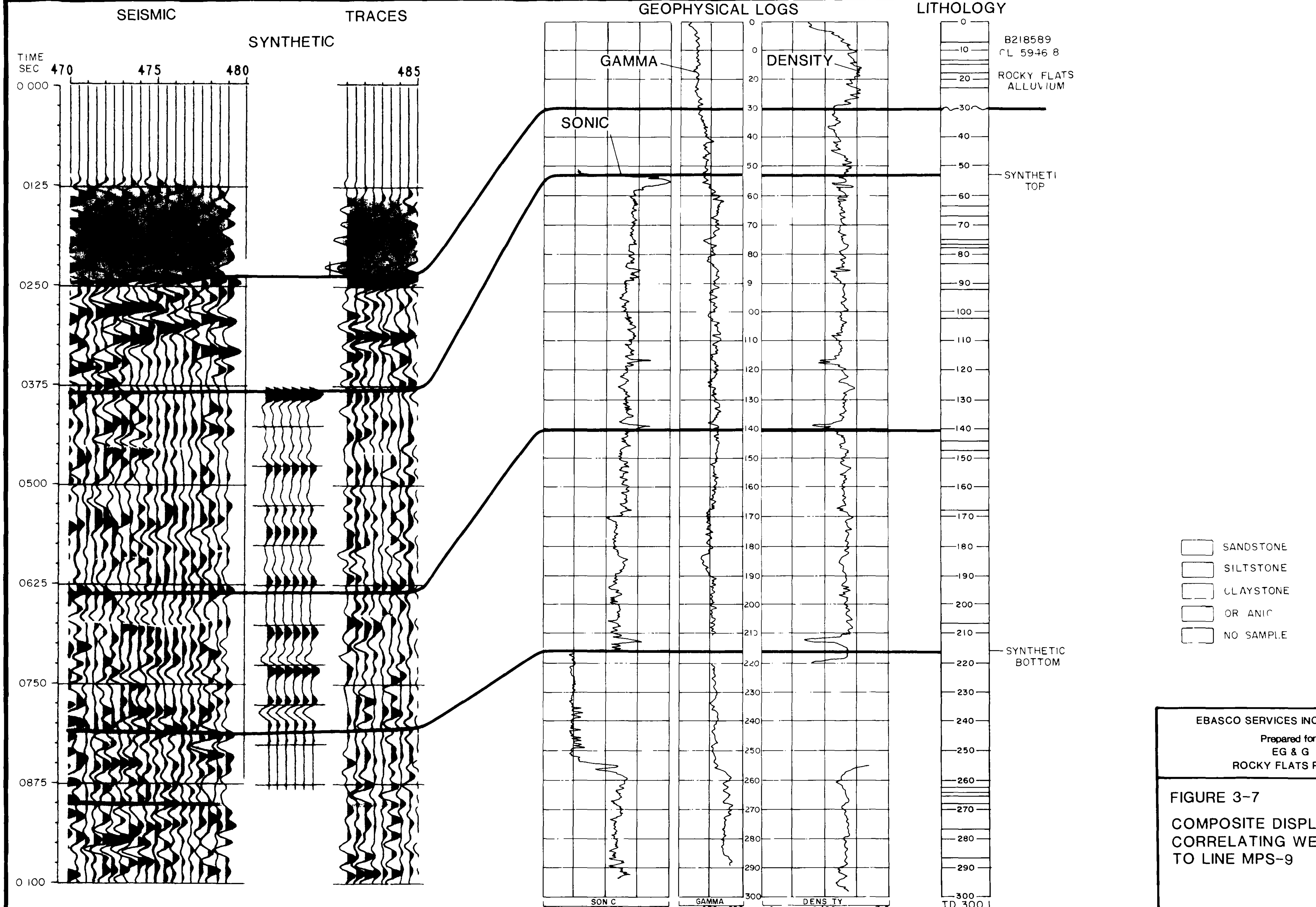

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FIGURE 3-7

COMPOSITE DISPLAY
CORRELATING WELL B218589
TO LINE MPS-9

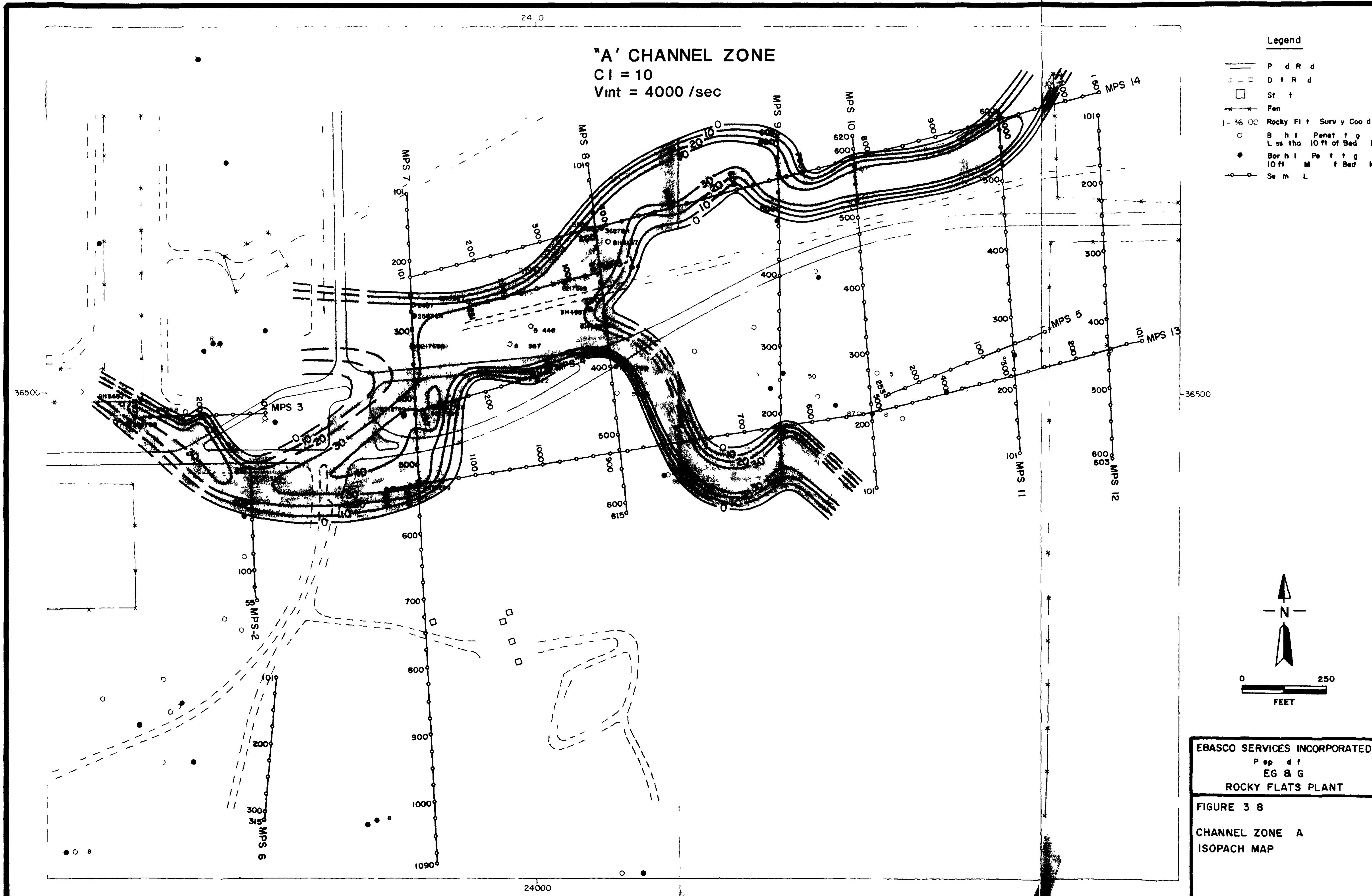

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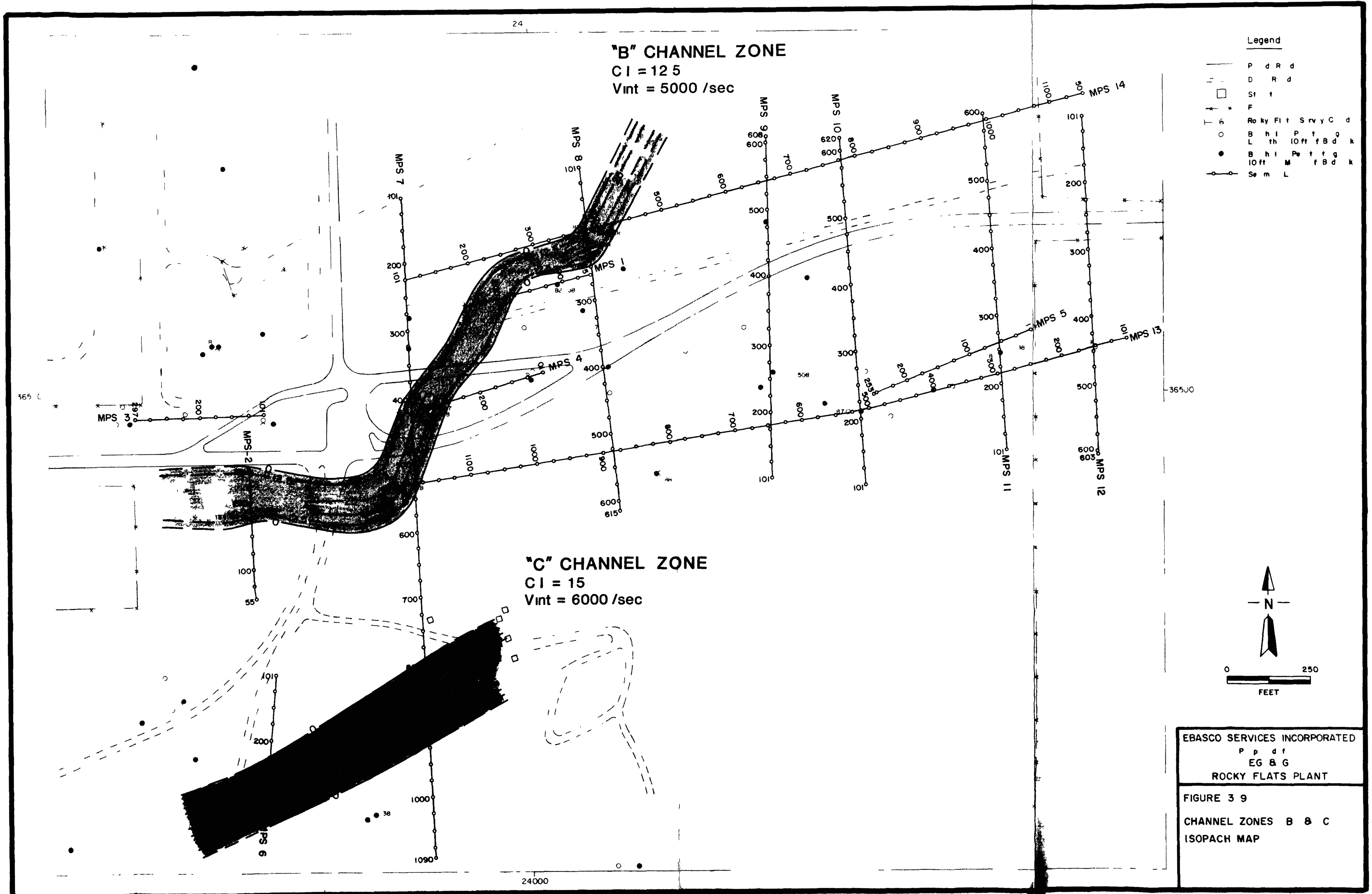
FIGURE 3 8

CHANNEL ZONE A
ISOPACH MAP


"B" CHANNEL ZONE
C I = 12 5
Vint = 5000 /sec
"C" CHANNEL ZONE
C I = 15
Vint = 6000 /sec
MPS 1
MPS-2
MPS 3
MPS 4
MPS 5
MPS 6
MPS 7
MPS 8
MPS 9
MPS 10
MPS 11
MPS 12
MPS 13
MPS 14
Legend
N
0
250
FEET
24000
36500
EBASCO SERVICES INCORPORATED
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ROCKY FLATS PLANT
FIGURE 3 9
CHANNEL ZONES B & C
ISOPACH MAP